Fermi National Accelerator Laboratory

TM-1605

A Novel Flattop Current Regulated Energy Discharge Type Pulsed Power Supply and Magnet Yielding 4.4 kGauss-meter for 6 Milliseconds

A. T. Visser
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

July 1989

Operated by Universities Research Association, Inc., under contract with the United States Department of Energy

TM #1605
2232.100

A.T. Visser
July 1989

X3273
MS #220

A NOVEL FLATTOP CURRENT REGULATED ENERGY DISCHARGE TYPE PULSED POWER SUPPLY AND MAGNET YIELDING 4.4 KGAUSS-METER FOR 6 MILLISECONDS

TABLE OF CONTENTS

1. SUMMARY

Most energy discharge power supplies obtain their bursts of power from the energy stored in charged capacitors when it is suddenly released into a load.

This note describes the design of a similar small 800 Joules energy discharge type power supply and magnet. The magnet gap is 2"x2"x25-1/2" long and produces about 4.4 kGauss-meters at a rate of 12 pulses per minute. Each pulse is current regulated at the top for a duration of 6 msec. and varies less than 0.6% of set value. Current regulation at flattop is obtained by switching a resistor in and out of the discharge circuit with an IGBT at a rate of about 5 kHz.

Most energy discharge systems produce half sine wave pulses, and current regulation is obtained by controlling the charge voltage at the energy storage capacitor, resulting only in a controlled peak current value of the half sine wave pulse. The current value at the top changes substantially during 6 msec. depending on the operating frequency.

Pulse peak current and voltage are 200A at 600V.

Automatic charge recovery makes it possible to operate the power supply from a 120V, 20A source.

The magnet is made from standard Silectron cores with a 2" gap cut into them. This type of magnet construction is economical to make and provides excellent frequency response. The magnet flattop field ripple can be substantially reduced by covering each pole face with a 1/32 thick aluminum sheet. Tests showing the effects of various metal thicknesses have been made. Magnet field ripple reductions of a factor of 4 are possible without making the magnet response too sluggish. The magnet has no vacuum tube.

The power supply and magnet are matched to allow the selection of easily available industrial electrical components. An interesting conclusion is that a long magnet at a low field requires less stored energy and is a better choice in this case.

The distance between the load and the power supply is about 125 ft. The power connection to the load is made with a 12/c #12

cable by connecting the three inner conductors to one magnet terminal and the nine outer conductors to the other magnet terminal. A multiconductor cable can be used as a very flexible "power coaxial cable" up to several kilovolts.

2. EQUIPMENT PARAMETERS

2.1 Magnet

Gap	-	2"Hx2-1/16"Wx25.5"L
Peak Current	-	200A
RMS Current, Tested	~	18A at 100°C hot spot, 40°C amb.
Peak Voltage	-	600V
Coil Insulation Class	~	155°C
Field	-	6.7 kG at 200A
Field	-	4.4 kGm at 200A
Coil Turns	-	140, AWG #9, ESSEX HGP
Coil Resistance	-	0.503 Ohm at 20° C
Magnet Inductance	-	16.5×10^{-3} H
Stored Energy	-	330 Joules at 200A
Magnet Weight	~	400 Lbs
Coil Hipot Test	-	2000 VDC

2.2 Power Supply

Type	-	Pulsed, flattop current regulated, energy discharge
Max. Stored Energy	-	800 Joules
Input	-	120V, 20A, 1 Phase
Output Pulse	-	200A at 600V
Operating Discharge Frequency	-	16Hz with 2.1
Pulse Rate	-	1 Pulse per 5 sec. continuous at 40°C ambient
Pulse Rate Limit Set	-	1 pulse per 4 sec.
Current Regulation Envelope peak to peak	-	0.6% of set value including peak to peak ripple, from 20A to 200A during 6 millisecond
Control Loc/Remote	-	20A/V, same as standard beamline DC power supply
Readback	-	20 A/V, updates every pulse
Firing pulse, remote	-	+5V, TTL, 1 μsec. wide
Delay from firing		

pulse to flattop start	-	10.2 msec.
Recovered Energy	~	40%
Size	-	R. Rack, 24"Wx30"Dx72"H
Additional Info	-	See test results, page 21

3. REQUESTED DESIGN REQUIREMENTS

Design and build a magnet and power supply that will produce 4 kGauss-meter pulses, 4 millisecond long. The magnet gap must be 2"x2", and the total magnet length can not exceed 36". The magnetic field needs to be regulated to within 1% during the 4 msec. period. There will be 6 pulses per minute, spaced 5 seconds apart. Each pulse has to be completed within a 200 msec. window between 5 second long slow spill periods.

The system will be used for neutrino fast extraction to the NK beamline for Experiment 782, and is popularly referred to as "Gordon's Ping".

4. CIRCUIT AND COMPONENT CHOICES

Let us first choose a circuit and then decide whether to use low voltage high current pulses, or high voltage and low current pulses, which will yield the same field integral BL. Several circuits were considered, but the circuit of Fig. 1 below, looks very attractive and simple, if we can do it.

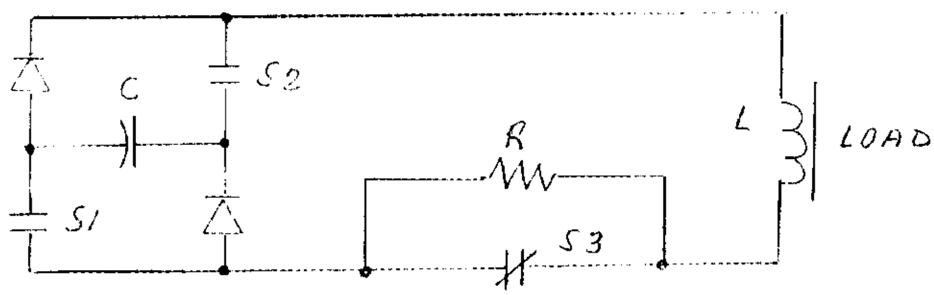


Figure 1
Current Regulated Energy Discharge Circuit

Here is how it works. Capacitor C is charged from a small DC charging supply. S1, S2 and S3 are switches. When S1 and S2 close C discharges into load L and the load current rises like a damped half sine wave until it reaches the required set value. At that time, switch

S3 opens and inserts R into the discharge loop, which makes the current drop. When the current gets too low, S3 closes again. If we do this fast enough (about 1kHz to 5kHz) than the discharge current looks like a half sine wave with the top sliced off and less than 1% top ripple. When the capacitor voltage is close to zero switches S1 and S2 open and the stored energy, which is now in the magnet, will flow back to C, except for the losses.

For switches S1, S2 and S3 we can use IGBT's (insulated gate bipolar transistors) which are available at ratings of 1000V and several hundred amp. at switching speeds in the order of 10 kHz. They are voltage controlled devices, requiring about + and - 17 VDC for on-off control. IGBT's are ideal for this circuit, as long as we can stay within their ratings. Fortunately, we have a lot of flexibility because the magnet design is not fixed at this time.

What can we conclude about the discharge frequency? The half sine wave discharge current must fit within the 200 msec. window and the flattop must be about 6 msec.

Thus: $2.5\text{Hz} < f < 83$ Hz. Frequencies higher than 24Hz are not practical. This is discussed later.

Note: The current of a 6Hz sine wave would fit within the 200 msec. window and stay within 1% for about 6 msec. around the peak. This low frequency operation requires a large L and C. This approach has not been further investigated, but it is probably feasible to make such a system.

We will continue with Fig. 1 and choose an operating frequency somewhere between 3Hz and 24Hz. The frequency choice will be goverened by practical choices for C, L, and the operating voltage. The peak current should be such that the flattop current value is about 0.9 times the unregulated peak current value. This is the case when the flattop duration t_f is 50^o electrical degrees long. The natural discharge frequency should therefore be about:

$$f = \frac{1}{7t_f}$$

A 6 msec. flattop requires therefore a natural discharge frequency of about f = 24 Hz or less. Higher operating frequencies are not too practical because the natural peak discharge current and thus the stored energy in the power supply, would have to be too high to cover the required flattop period. The frequency should therefore be 3Hz $< f <$ 24Hz.

What can we tell about the magnet? The gap is 2"x2", less than 36" long, and produces 4 kG-m. Thus, a 36" long magnet needs about 4 kG field and a 12" long magnet needs 12 kG. A high field magnet however, requires more ampere turns and more stored energy for the same Bdl. How can that be true? The stored energy of a magnet is:

$$\frac{1}{2}L\,i^2 \quad = \quad \frac{1}{2}\frac{N\Phi}{i}\,i^2 \qquad \Phi = \text{magnet flux}$$

If we ignore the leakage field we can write:

$$\frac{1}{2}L\,i^2 \quad = \quad \frac{1}{2}NBAi \qquad \begin{array}{l} A = \text{gap area} \\ B = \text{field strength} \end{array}$$

Further we can write:

$$B \quad = \quad \mu_o H \qquad H = \text{Amp Turn}/_m$$

$$H \quad = \quad \frac{Ni}{G} \qquad G = \text{Gap height}$$

This yields:

$$i \quad = \quad \frac{G\;\;B}{\mu_o N}$$

We can now express the stored energy as a function of the gap volume and field strength

$$\frac{1}{2}L\,i^2 \quad = \quad \frac{1}{2}\frac{NBAGB}{\mu_o N}$$

$$\frac{1}{2}L\, i^2 = \frac{1}{2}\frac{B^2 V}{\mu_o} \qquad V = \text{gap volume}$$

From this we can conclude that a short magnet requires more stored energy for the same Bdl. Say that a 1' magnet requires a field 3B with gap volume V and a 3' magnet a field B with a gap volume 3V. The 1' short magnet has stored energy:

$$\frac{1}{2}L\, i^2 = \frac{1}{2}\frac{(3B)^2 V}{\mu_o} \qquad \text{Joules}$$

$$\frac{1}{2}L\, i^2 = 4.5\,\frac{B^2 V}{\mu_o} \qquad \text{Joules}$$

The long magnet has stored energy:

$$\frac{1}{2}L\, i^2 = \frac{1}{2}\frac{B^2 3\, V}{\mu_o} \qquad \text{Joules}$$

$$\frac{1}{2}L\, i^2 = 1.5\,\frac{B^2 V}{\mu_o} \qquad \text{Joules}$$

There is a factor of 3 difference in stored energy.

Increasing the length of a magnet by a factor x decreases the stored energy by a factor $^{1/x}$ for the same Bdl. This is important because we can control the required stored energy by choosing a different magnet length. Generally, we are better off choosing a longer magnet and thus a lower B, because we need less ampere turns and substantially less stored energy. It takes however more magnet steel, but for the chosen design this was only about $40 per inch magnet length.

A 25.5" (64.77 cm) long gap, 2" (5.08 cm) high and 2-1/16" (5.24 cm) wide at 6.18 kGauss produces 4 kGm and has a stored energy of:

$$\frac{1}{2} L i^2 = \frac{1}{2} \frac{B^2 V}{\mu_o}$$

$$= \frac{1}{2} \frac{0.618^2 x 0.6477 x 0.0524 x 0.0508}{4\pi x\ 10^{-7}} = 262 \text{ Joules}$$

This amount of energy, multiplied by 1.25 for current regulation, times 1.25 for a Bdl safety factor of 10% and times 1.2 for losses amounts to about 500 Joules, which needs to be stored in the energy storage capacitor. It appears, also from final test results, that for this type of current regulated discharge system the power supply stored energy needs to be at least 2 times the magnet stored energy, to allow for regulation, losses, and a safety factor for stray fields, etc. We will use this for a preliminary estimate. Storing the energy at around 500V allows the use of a 1000V IGBT with a voltage safety factor of 2. The size of C can now be estimated, assuming we need to store 500 Joules.

$$1/2\ C\ 500^2 = 500$$
$$C = 0.004 \text{ F}$$
$$C = 4000\ \mu\text{F}$$

C = 4000 μF puts us in the ballpark. We have 2230, 1000 μF, 1000 V peak capacitors, as leftovers from another project, and will use 2 of these in parallel.

We have now chosen the amount of stored energy to be about 500 Joules and thus the magnet has to be about 25" long at 6.2 kGauss at 260 Joules.

The thing left to do now is to find out how many turns the magnet needs and to design the coil. A maximum current limit of 200A is required by the IGBT rating. The magnet gap is 2". We will make the magnet from commercially available tape wound Silectron cores, which are a catalogue item from Arnold Engineering. Arnold will cut a 2' gap in each core. Four cores in a row will make a 25.5" long magnet and require 6.18 kG for 4 kGm. We can now calculate the required gap ampere turns AT for 6.18KG as follows:

$$B = \mu_o H$$

$$H = \frac{.618}{4\pi x 10^{-7}} = 491788 \quad AT/_{m}$$

$$AT/_{2inch} = 24,982$$

$$N = 140$$

The ampere turns for the magnet steel are negligible.

$$i = 178.5 \text{ A (10\% safety factor for currents to 200A)}$$

$$L = \frac{N\Phi}{i}$$

$$L = 16.5 \times 10^{-3} H$$

The operating frequency of the discharge circuit is about:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{16.5x10^{-3}x4460x10^{-6}}}$$

$$f = 18.6Hz.$$

All these choices indicate that we can build the circuit of Fig. 1 using IGBT's rated 1000V, 200A.

We must now choose the coil wire size so that it will not run hot. The coil needs 140 turns and receives 6 pulses per minute at 200A peak. Let us be conservative and say that the coil receives 6 square wave pulses per minute, 20 msec. long at 200A peak. The equivalent RMS value of such a pulse train is:

$$I_{RMS} = 200\sqrt{\frac{6 \times 0.02}{60}}$$

I_{RMS} = 8.9 Amp.

Thus the coil must be able to handle 8.9 Amp DC continuous. Each coil must not be higher than 1-3/4", otherwise we cannot slip it through the 2" magnet gap for installation, but must be taller than 1" for mounting support to the side of the pole.

The current density in the coil wire determines the losses and thus the temperature rise. How do we choose? The current sheet around the gap carries 140 x 8.9 = 1246 Amp. From publication, "Anaconda: Copper metal electrical conductors, C-25" we find that 1/2 x 3 copper, rectangular bus bars in free still air rise 30°C at 1230 Amp. This will have to be the approximate coil shape. The coil will run hotter because its surface is partially covered by supports and insulation. If 50% of the coil surface is covered it will run twice as hot. The 1/2x3 bar at 1230 Amp. runs at a current density of 820 $A/_{inch^2}$ at 30°C temperature rise.

We may estimate that half the coil surface is covered by supports and the coil is expected to run at about 60°C rise at a current density of 820$A/_{inch^2}$. The coil wire cross section must be about:

$$820\ S = 8.9$$
$$S = 0.01085\ \text{inch}^2.$$

Choose coil wire AWG #9 square, ESSEX HGP200, 200°C, polyester amide, imide, film insulated, with 0.0131 inch^2 cross section. The final coil cross section is about (SH 1 B) 3-1/2"x3/4". The coil will be put together with Scotchply, Armorflex and Epoxy, which have a finished temperature class rating of 155°C. The hottest operating spot in the coil is estimated to be:

40^oC (ambient)+60^oC(rise)+20^oC(hot spot allowance) = 120^oC.

This is well below the finished coil temperature class. We will install a 90^oC klixon at the coil surface for an overtemperature interlock.

The value of resistor R has not been chosen. Obviously R has to be larger than 0, but smaller than 3 Ω if we want to preserve a voltage safety factor of 2 for switch 3. At worst we could lose control at 200A and all the current would have to go through R, creating 200R volts. Ignoring the circuit resistance we can say that for the lower limit, at the instant we go into flattop, the iR drop has to equal at least the remaining charge voltage at C, because the magnet $L\frac{di}{dt}$ is than zero.

The remaining charge is the highest at 200A operation. At the beginning of 200A flattop:

$$\frac{1}{2} L\ i^2 = \frac{1}{2}\ 16.5 \times 10^{-3} \times 200^2$$

$$\frac{1}{2} L\ i^2 = 330 \text{ Joules}$$

has been transferred from the storage capacitor to the magnet. The storage capacitor needs to have about 2 times more stored energy than the magnet to allow for flattop current regulation and losses. There is thus about 300 Joules left in the capacitor at a charge voltage V of:

$$1/2 \times 4460 \times 10^{-6}\ V^2 = 300$$

$$V = 370 \text{ Volt.}$$

The resistor R should therefore be larger than 1.85 Ω and smaller than 3 Ω. The resistor R should be non-inductive and conservatively rated so that it will not fail open. R was chosen to be 1.67 Ω, 300 Watt with a good snubber at switch 3.

We have now chosen all the major building blocks. Attached drawings on pages 1A, 1B and 2 show the final choices and calculated values. The magnet shown on page 1A shows that it is made from C-shaped Silectron cores. These are standard size transformer cores as made by Arnold Engineering and probably various other core manufacturers. The manufacturer cut the 2" gap in it at a total cost per core of less than $200 each. The cores are epoxy cast in a cradle for gap alignment after which the saddle coil is installed. A saddle coil is used to keep the stray field around the gap as small as practical. The coil needs to be securely supported because it is pulsed. This type of magnet steel construction could possibly be used to construct economical beamline trim magnets with a 4" wide gap, by installing the cores back to back. There are small variations (~1/32") in the gap of the cores we received, but this could be improved by better cutting techniques. For many applications it does not matter.

The coils were built in-house on a small fixture. It took about 2 man-weeks per set after we learned how to do it.

The drawing on page 2 shows the final circuit and calculated values. The ringing frequency of an RLC circuit is calculated as:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

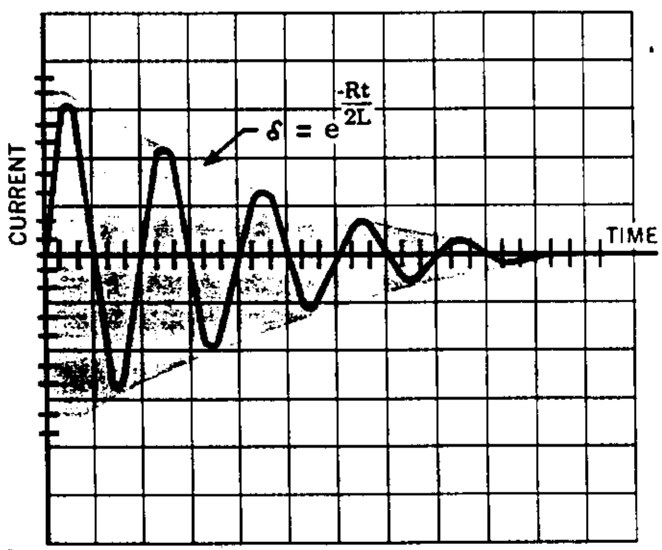


Figure 2

The instantaneous value of current in an oscillatory RLC circuit, as shown in Fig. 2, is:

$$i = 2\pi fCV\exp\left(-\frac{Rt}{2L}\right)\sin 2\pi ft,$$

where

$$2\pi fCV = \text{undamped peak current}$$

$$\exp\left(-\frac{Rt}{2L}\right) = \text{damping factor } (\delta)$$

$$\sin 2\pi ft = \text{oscillatory function}$$

$$t = \text{time}$$

The peak discharge current occurs at 1/4 the period of the circuit ringing frequency. At peak current the oscillatory function is unity, and the expression for peak current is:

$$I\ \text{peak} = 2\pi fCV\exp\left(-\frac{R}{8Lf}\right)$$

The total resistance of the discharge circuit is calculated to be 0.67 Ω and it has a calculated ringing frequency of 18.2 Hz. For a peak discharge current of 220 Amp. we can estimate a charge voltage of 560 volts. These values are all within the previously discussed limits.

The current is measured with a LEM current transductor. An external (or internal) reference determines the operating current and also controls the level of the charge voltage at C1. This is necessary because with a high charge voltage and low demand current, the resistor R = 1.67 Ω would be too small to make the current drop at the start of flattop. The tracking is such, that the charge at C1 would yield about a 10% larger unregulated peak current than the programmed flattop value. This tracking is automatically maintained over the full range of flattop currents.

If the reference voltage is substantially reduced between pulses, than the power supply will not regulate for a few pulses because of the excessive recovered charge. This is not a problem for this application. The power supply and load ringing frequency determine the elapsed time (10.2 msec.) between the firing pulse and the start of flattop. The duration of flattop can be slightly adjusted by changing the charge voltage. It is set up to yield about 6 msec. flattop. The turn-off time of switches 1 and 2 is internally set to occur close to zero C1 charge voltage. At that time the remaining C1 charge cannot escape anymore. The magnetically stored energy will then automatically be added to the remaining C1 charge at the correct polarity via the diodes. Charge recovery reduces the required operating power drastically, so that the power supply can be operated from a 115V, 20A single phase circuit. The DC charging supply always remains connected to C1 via 100 Ω isolation resistors and makes up the system losses during the 5 second rest period. The D.C. pulsed power is transmitted to the load via a multiconductor cable, in this case, a 12/c #12. The 3 inner wires and 9 outer wires can be used as a very convenient coaxial transmission line. Cables with a higher number of conductors or larger conductors could be used for larger distances. It should be possible to operate 600 VAC cables like this up to about 5 kV. They are very handy because of their flexibility and economy. The power supply is equipped with overcurrent, overtemp, and a ground fault detector. Current readout is available from a sample and hold. The control layout is the same as for a standard beamline power supply, with a scale factor of 20A/V. The only extra command we use, is the firing pulse to start the discharge. Firing pulses within a 4 second window will be ignored.

Detailed power supply schematics are shown on drawing sheets 2 through 12. A number of component choices were made because they were available as leftovers from other jobs, or we wanted to match existing parts (spares) in other equipment.

5. CIRCUIT COMMENTS

The circuit components around C1 in a bridge configuration need attention, although it looks very simple. Switches 1 and 2 are basically operated in series, and must switch simultaneously. Voltage sharing during switching may not be perfect. It is therefore, that we choose to switch them off at a low leftover voltage on C1. Good snubbers should be installed. The voltage to ground (input to firing circuit of opto-coupler) S2 changes very rapidly ($\sim 1000\mathrm{V}/_{\mu\mathrm{sec}}$.) Capacitive coupling between the opto-coupler input to output can cause switching (oscillation) of IGBT's 1 and 2. The spec's on some opto-couplers are not always clear in this respect. Good shielded opto couplers should be used. Fiber optics or magnetic coupling is recommended for higher operating voltages. We had lost 2 IGBT's at higher voltages until we understood what was happening. A better opto coupler cured the problem. Voltage sharing between IGBT 1 and 2 seems very good, but each is rated to handle the full charge voltage with a voltage safety factor of 2.

Each diode has to block the full charge voltage when IGBT 1 and 2 switch on. Care should be taken to build the least amount of stray inductance into the discharge circuit. The bypass circuit around IGBT 3 must have very low inductance, and an effective snubber must be installed. The wire wound, inductive, snubber resistors have a small jacket of Cu foil installed around them which makes them practically non-inductive. In general, we had very little trouble with this circuit. A lot of testing can be done at low power levels. The opto coupler problem was the hardest to solve because it showed up only at the higher power levels where it could destroy an IGBT.

Some comments about another possible circuit are mentioned hereafter.

The circuit of Fig. 1 could be developed into a more powerful system using SCR's and IGBT's as in Fig 3.

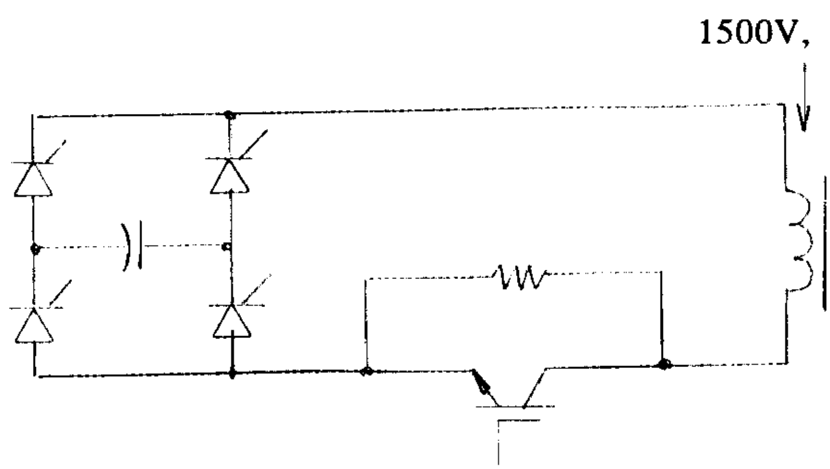


Figure 3

C is charged forward from one small power supply and reverse from another. Start out with C being charged forward and fire all 4 SCR's at the same time. C will now discharge through the load and recover in reverse. The reverse supply adds the losses, fire all 4 SCR's again and C discharges into the load in the same direction but will now recover in the forward direction, etc. Much more powerful SCR's than IGBT's can be economically purchased.

For each direction we would need to fire only 2 SCR's, but firing all 4 is much simpler to control. Only the forward biased SCR's will conduct. The regulating IGBT could be coupled into the load with an additional turn(s) if the currents are too large. This is an interesting circuit for powerful applications.

6. TEST RESULTS

All three magnets and power supplies have been tested and perform the same. The power supplies perform well within the required performance limits. Attached Fig. 4 shows a picture of the magnet during construction. The magnet coil surface temperature rises 11°C with a continuous 200A pulse every 5 sec. Running the magnet for a day at 18ADC causes a coil resistance increase of 17%, or an average $\Delta T = 43°C$. This can be calculated from:

$$R_{HOT} = R_{COLD}\,(1+0.004\Delta T).$$

The hottest spot in the coil is 40° (ambient) + 43°C (rise) + 20° C.(hot spot allowance) ~ 100°C at 18A RMS. The coil design is thus conservative for this application.

Page 20 shows the magnet field distribution in the gap. At 200A we reach 6.7 kG as figured. This is a somewhat complicated test because the field lasts only 6 msec.

The power supply and magnet performance are tabulated on page 21 The required charge voltage for 200A is about 100V more than figured. The total peak to peak flattop variation is less than 0.6%. Power supply "set to" repeatability and temperature regulation are excellent and the overall system performs well within the 1% requirement. Operation at currents lower than 20A is unreliable.

Page 22 shows a number of very interesting power supply current and voltage pictures. The peak to peak current ripplle is about 0.4% and also shows up at the same magnitude in the magnet field as shown on page 23 in the field ripple for bare poles. We had to make some fast electronics around a Hall chip in order to make the magnet field ripple tests. There is some noise pickup due to the fast switching voltages. Remember that the field rises to about 6KG in a few msec. and that we want to be able to see a few Gauss changes during the 6 msec. flattop. The actual field ripple is indicated by the term "TRUE RIPPLE" on pages

23 and 24. The magnet field and current ripple look very much the same, as shown for a bare pole at 160A, pages 23 and 24. The field ripple can be reduced by covering the poles with a thin metal plate. Eddy currents in the plates will try to cancel magnet field variations. A thick plate will ruin the magnet pulse response, but thinner plates will act like a low pass magnetic field filter. There is some very interesting test data on pages 23 and 24 showing the effects of various pole face cover thicknesses. It is possible to reduce the magnet field ripple a factor of 4 with 1/32 thick aluminum sheet metal installed at each pole face. Thicker covers make the magnet pulse response too slow, so that there is no flattop field left.

The first power supply was run on and off for several months at full power, in between various tests. The equipment seems to be very reliable.

7. ACKNOWLEDGEMENTS

No equipment can perform better than the way it is put together, tested and developed. It takes time and effort to bring an idea to a successful operating system. Walt Jaskierny deserves a lot of credit for many improvements to the electronics, the packaging and testing. I am also very grateful for the help of the mechanical technicians, supervised by Don Carpenter, for their help in building the magnets and coils. This was strictly an EED effort.

8. OPERATING PROCEDURES

The power supply is operated from local or remote like a standard beamline D.C. power supply. In addition, it needs a 5V firing pulse to get started. Every firing pulse gives one power supply output pulse. The power supply has a built-in pulse rate limit. Firing pulses less than 4 seconds apart do not come through.

It takes time (10.2 msec.) for the power supply to reach the programmed flattop current value.

1. <u>Set the power supply firing pulse 11 msec. ahead of the start of the fast spill beam pulse.</u>

2. Each power supply flattop pulse is 6 msec. long.

3. Set the required current at $20A/V_{reference}$. 180A (9V reference) yields 4kGmeter. The power supply operating range is 20A to 200A.

4. The power supply samples the center value of each flattop current with a "sample and hold" and provides $1V/_{20A\ flattop}$ for remote readback. The readback updates every pulse.

CAUTION

The power supply contains a lethal amount of stored energy. This stored energy is automatically removed when the power supply doors are opened. A capacitor shorting/grounding stick is provided and must be applied before working on the equipment. Power supply lock-out facilities are provided at the circuit breaker of the charging supply.

Fermilab safety lock-out procedures must be followed, when servicing the equipment.

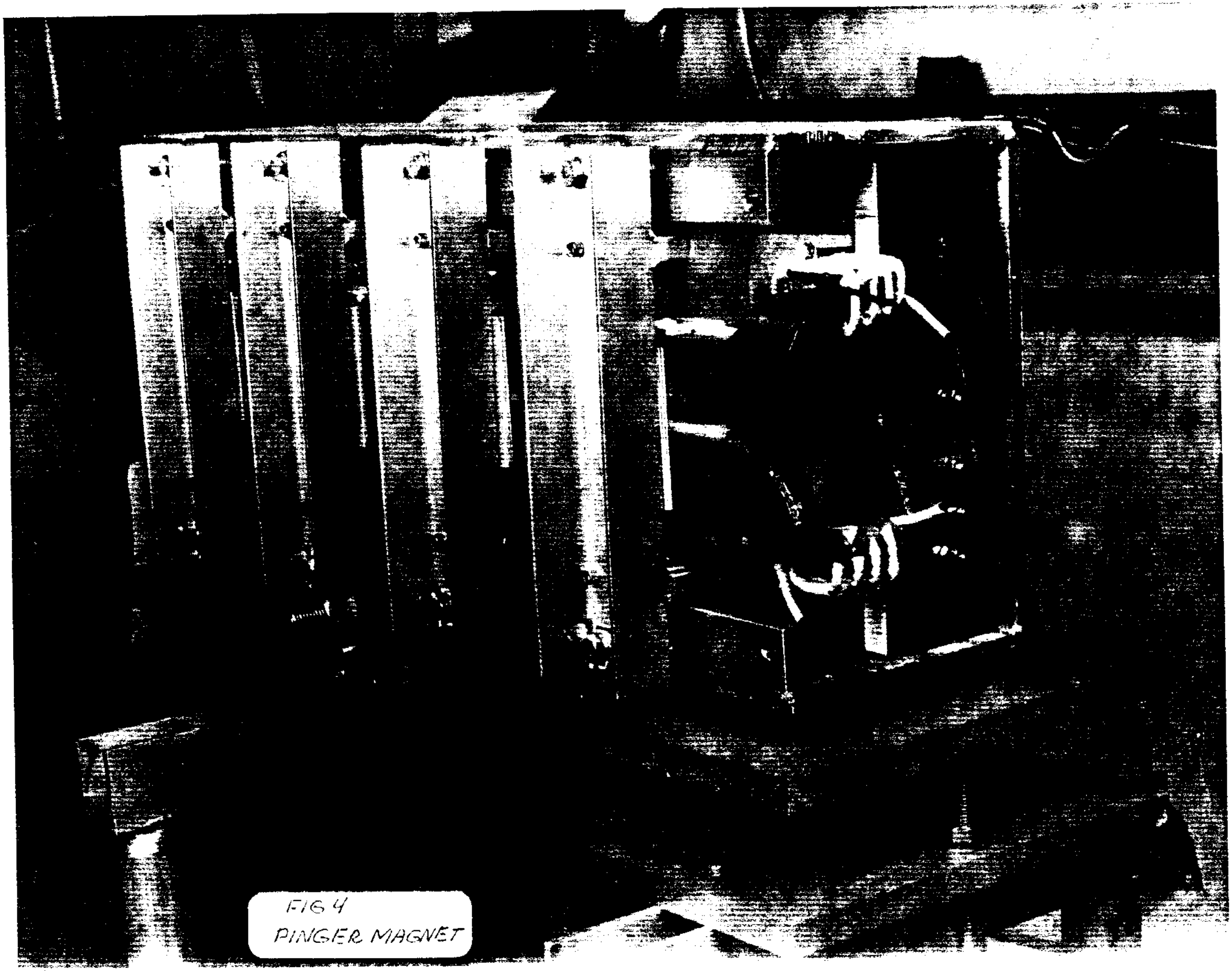
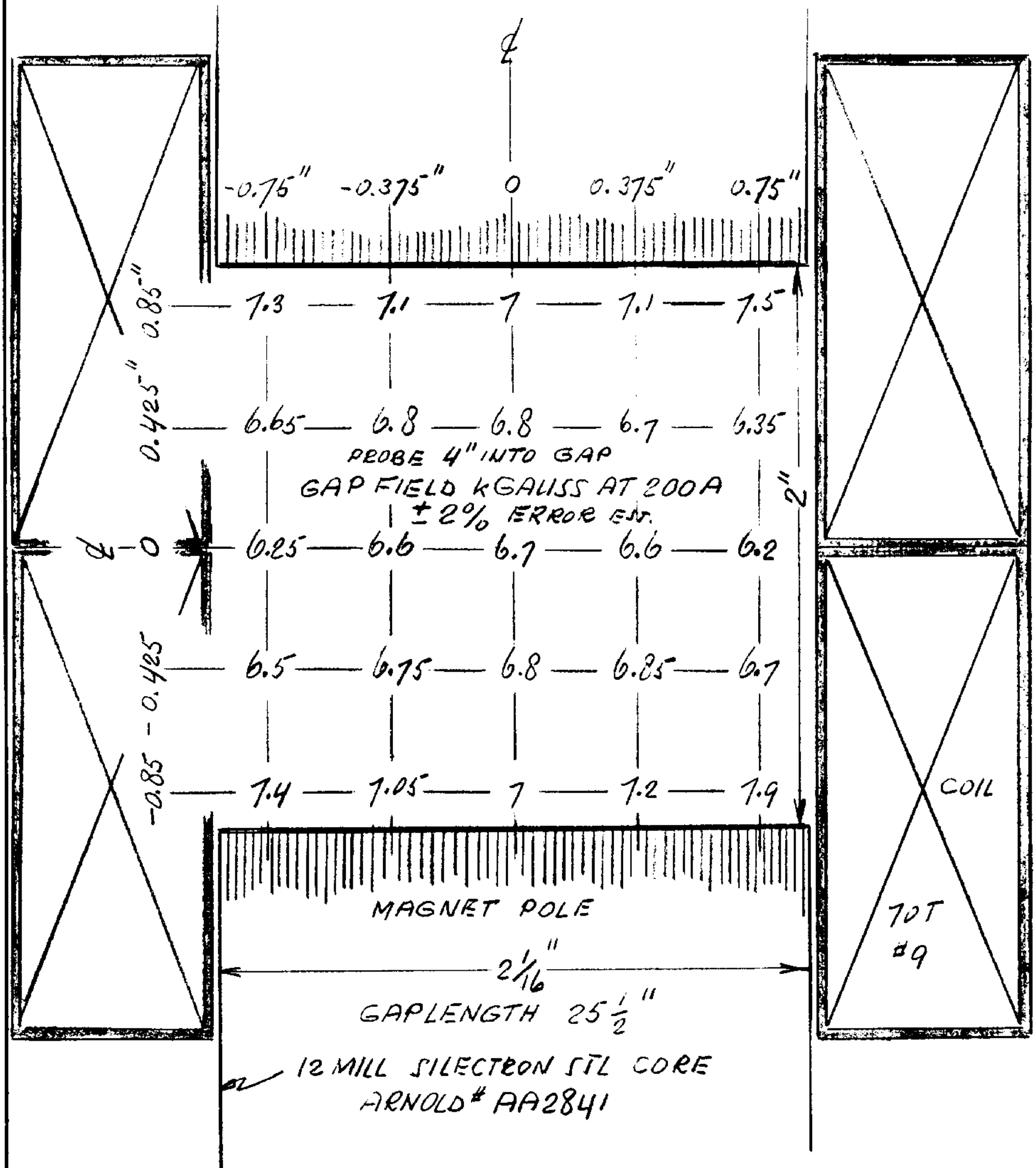


FIG 4
PINGER MAGNET

NATIONAL ACCELERATOR LABORATORY
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
EED-BS	PING 782	TM 1605	20

SUBJECT	NAME
NEUTRINO FAST SPILL, GORDON'S PING MAGNET FIELD DISTRIBUTION IN GAP AT 200 A	W. JASKIERNY/A.VISSER
	DATE: 7/12/89
	REVISION DATE:



SUBJECT: NEUTRINO FAST SPILL, GORDON'S PING MAGNET AND POWER SUPPLY TEST DATA

NAME: W. JASKIERNY / A. VISSER
DATE: 7/12/89
REVISION DATE:

1) SCOPE SET: -3 dB AT 30 kHz   W. JASKIERNY 7/12/89

MAGNET FIELD (kGAUSS)	MAGNET CURRENT SET 20A/V (AMP)	FLATTOP LENGTH (MILLISEC)	FLATTOP START DELAY FROM t_{FIRE} (MILLISEC)	FLATTOP RIPPLE P TO P AT FREQ 1) (AMP. AT kHz)		FLATTOP DROOP (AMP.)	FLATTOP TOTAL ΔI 1) P TO P OF SET VALUE (%)	CAPACITOR CHARGE (VOLT)	CAPACITOR RECOVERED CHARGE (VOLT)	DISCHARGE FREQ. (Hz)
6.7	200	4.5	11	0.5	5	0.3	0.4	658	400	15.6
5.35	160	6	10.2	0.5	4.55	0.2	0.4	527	330	16.1
4	120	6	10.2	0.44	4.55	0.06	0.4	396	250	16.1
2.75	80	6	10.2	0.36	3.57	0.14	0.6	264	170	16.1
1.4	40	6	10.3	0.24	3.1	0	0.6	133	84	16.4
0.71	20	5.6 TO 6	10.2 TO 10.4	0.14	2.6	0.04	0.9	67	45	17

PULSE TO PULSE VARIATION & REGULATION — < ± 50 mA PER DAY

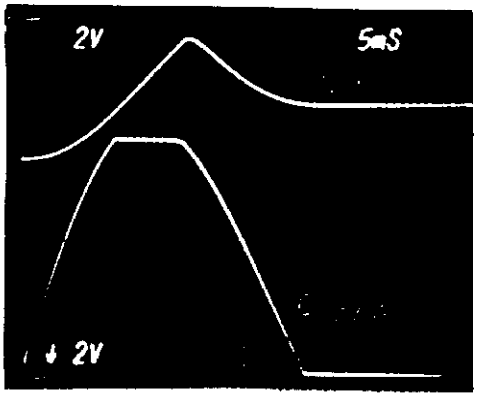
SET TO REPEATABILITY ———— < ± 50 mA

TEMPERATURE REGULATION ———— < 50 ppm/°C, ESTIMATE

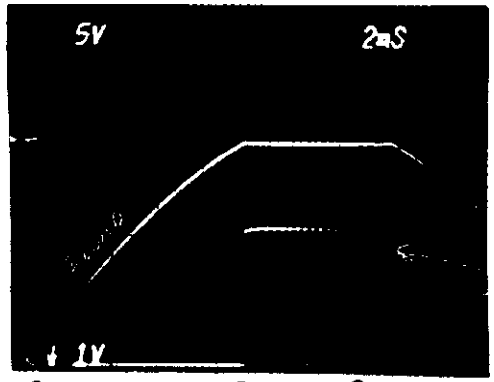
NOTE: ALL TESTS WITH 145 FT 12/C LOAD CABLE, 5 SEC. REP RATE, 116 VAC
T_{OFF} SET AT 18 mSEC.
MAGNET CURRENT SET TO, READBACK — 20A/V

NATIONAL ACCELERATOR LABORATORY ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	EED - 85	PING, 782	TM 1605	22

SUBJECT	NAME	DATE	REVISION DATE
NEUTRINO FAST SPILL, GORDON'S PING POWER SUPPLY CURRENT AND VOLTAGE PICTURES	A VISSER / JASKIERNY	7/14/89	

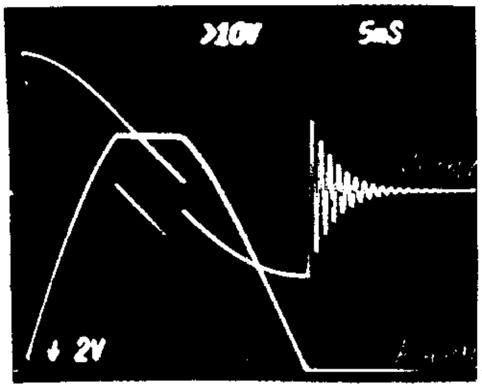


— 0
V_C 200 V/CM
— 200A
$I_L = 200 A_{pk}$
40A/CM
— 0

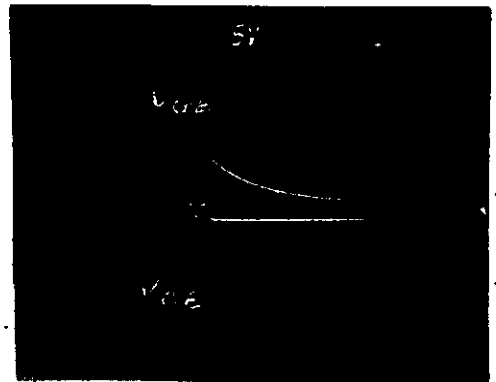


I_L 100A
— OFF +15V
IGBT 3
— ON 0

REGULATOR OUTPUT TO IGBT 3

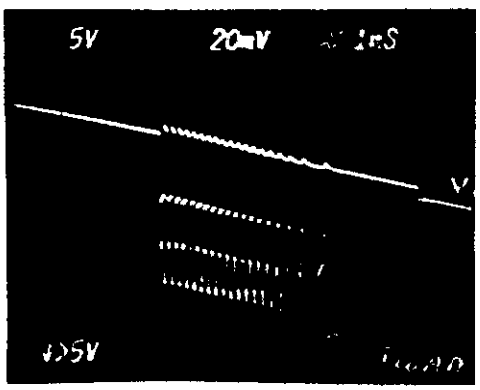


V_L 200V/CM
— 0
I_L-200A pk
— 0



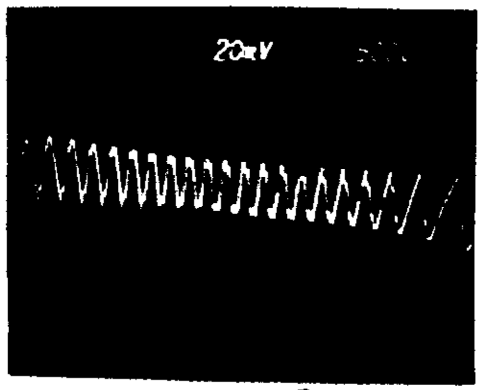
V_{GE} 15V/CM
— 0
— 0
V_{CE} 50V/CM

T_{OFF} IGBT1 AT TURNOFF



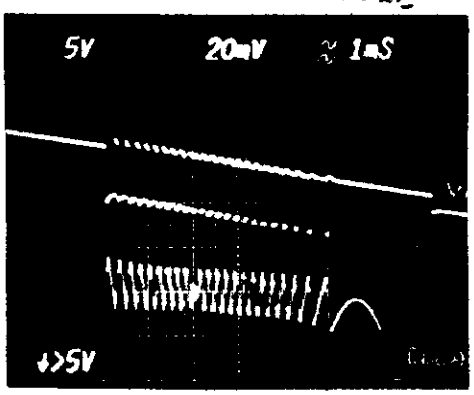
V_L 250V/CM
— I_L = 200A
0.4 A/CM

FLATTOP, I_{RIPPLE} ~0.3%



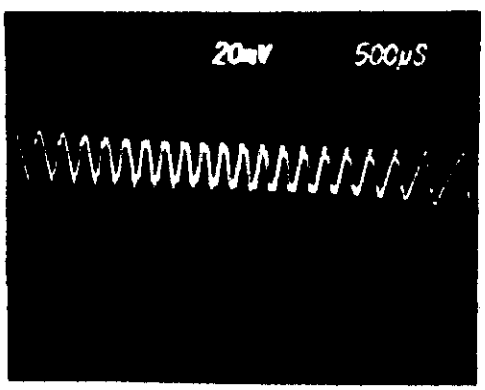
I_L = 200A
0.4 A/CM

FLATTOP, I_{RIPPLE} ~ 0.3%



V_L 250V/CM
— I_L=160A
0.4A/CM

FLATTOP, I_{RIPPLE} ~0.4%

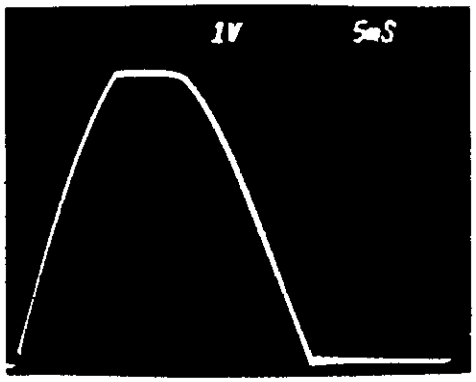


I_L=160A
0.4 A/CM

FLATTOP, I_{RIPPLE} ~0.4%

NATIONAL ACCELERATOR LABORATORY ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	EED-85	PING, 782	TM1605	23

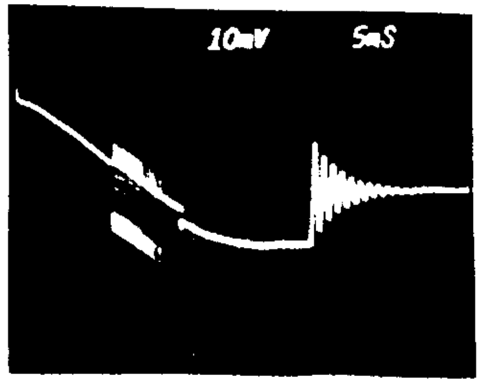
SUBJECT	NAME	DATE	REVISION DATE
NEUTRINO FAST SPILL, GORDON'S PING EFFECT OF METAL POLE FACE COVER THICKNESS ON MAGNET FIELD RIPPLE DURING FLATTOP	A VISSER, JASKIERNY	7/17/89	



MAGNET FIELD AT 200 A

1KG/CM

BARE POLE

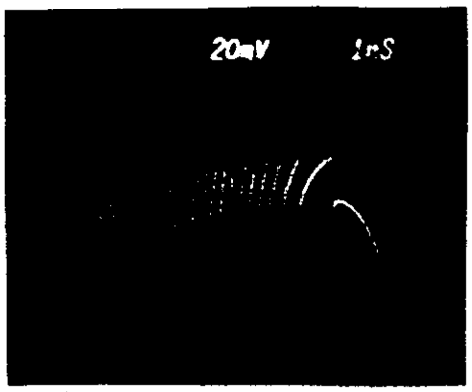


AT 200 A

PROBE PARALLEL TO FIELD — 0

10 G/CM

GAUSSPROBE EL. PICKUP NOISE, BARE POLE



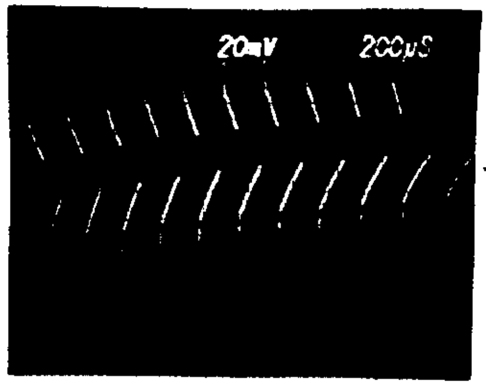
AT 200 A

TRUE RIPPLE

6.7 kG

20 G/CM

BARE POLE FIELD RIPPLE ~ 0.4%

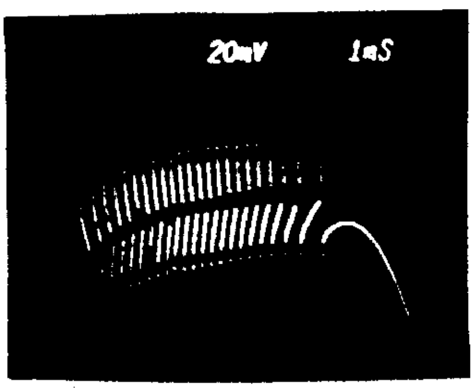


AT 200 A

TRUE RIPPLE

20 G/CM

BARE POLE FIELD RIPPLE ~ 0.4%

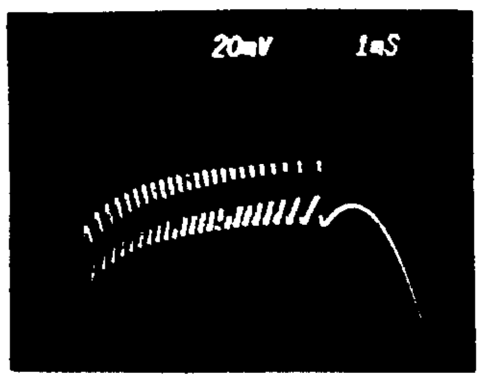


AT 160 A (5,4 kG)

TRUE RIPPLE

20 G/CM

BARE POLE FIELD RIPPLE ~ 0.4%



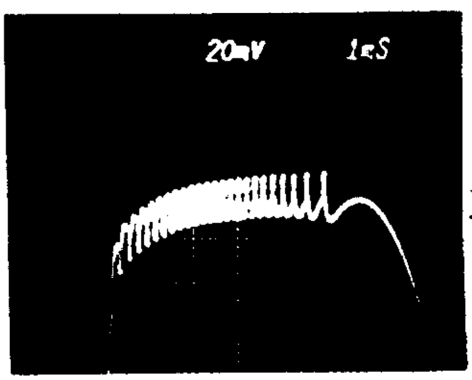
AT 160 A

TRUE RIPPLE

20 G/CM

RIPPLE ~ 0.2%

COVER BOTH POLE WITH 1 OZ. P. CARD MAT.



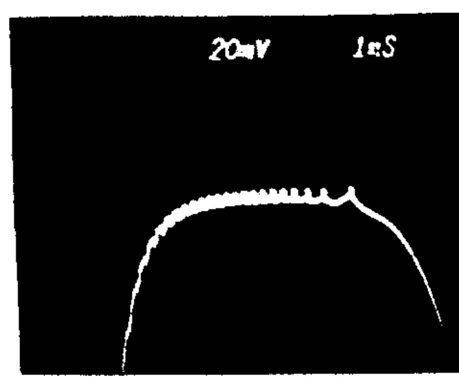
AT 160 A

TRUE RIPPLE

20 G/CM

RIPPLE ~ 0.2%

COVER BOTH POLES WITH 2 OZ. P. CARD MAT.



AT 160 A

TRUE RIPPLE

20 G/CM

RIPPLE ~ 0.05%

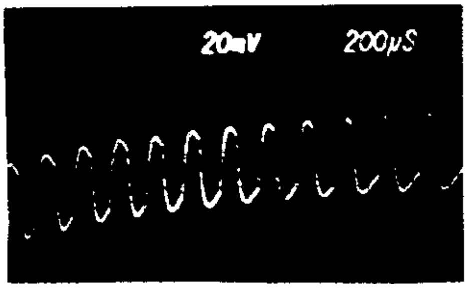
COVER BOTH POLES 1/16 THICK AL

NATIONAL ACCELERATOR LABORATORY

ENGINEERING NOTE

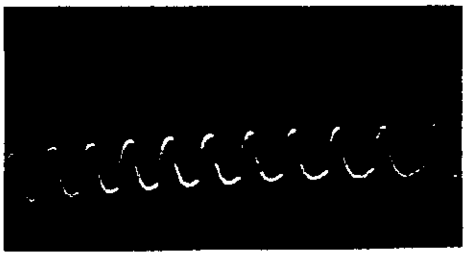
SECTION	PROJECT	SERIAL-CATEGORY	PAGE
EED-85	PING, 782	TM 1605	24

SUBJECT	NAME
NEUTRINO FAST SPILL, GORDON'S PING EFFECT OF METAL POLE FACE COVER THICKNESS ON MAGNET FIELD RIPPLE DURING FLATTOP	A VISSER / JASKIERNY
	DATE: 7/17/89 — REVISION DATE:



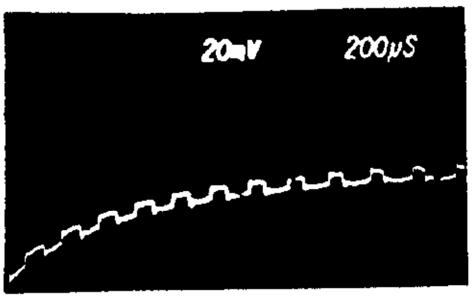
AT 200A
20 G/CM
TRUE RIPPLE
RIPPLE ~ 0.2%

1 OZ P.C. MAT. BOTH POLES



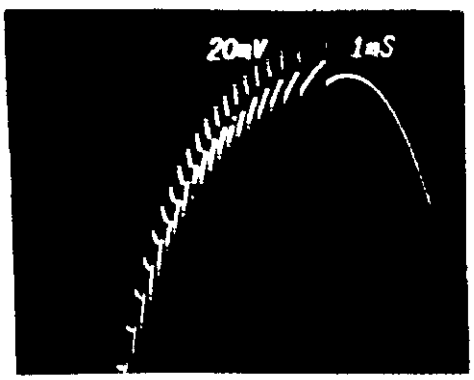
AT 200A
20 G/CM
TRUE RIPPLE
RIPPLE ~ 0.15%

2 OZ. P.C. MAT BOTH POLES



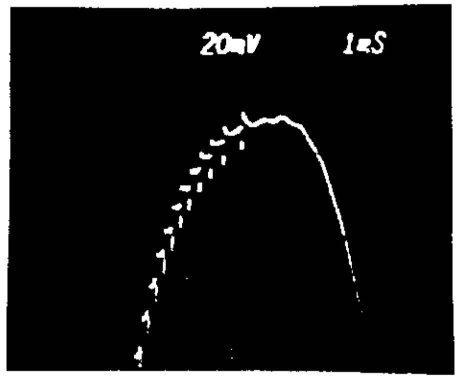
AT 200A
20 G/CM
RIPPLE ~ 0.06%

1/16 THICK AL. BOTH POLES



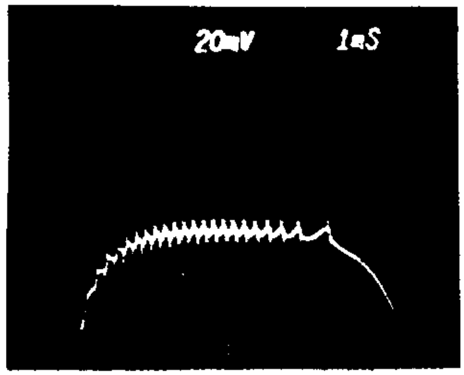
AT 160A
20 G/CM
TOO THICK! NO FLATTOP

3/32 THICK CU AT 1 POLE



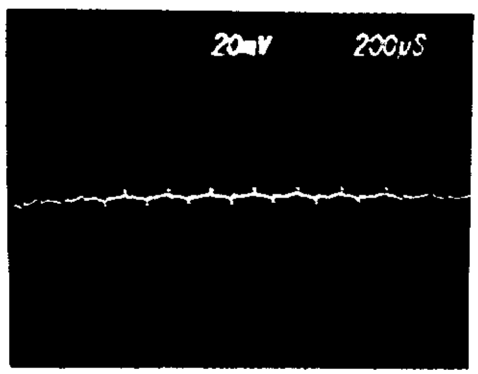
AT 200A
20 G/CM

1.9" O.D., 1/16 WALL AL. BEAMPIPE



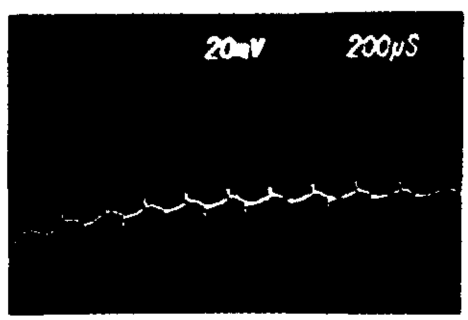
AT 160A
20 G/CM
RIPPLE ~ 0.1%

1/32 THICK AL BOTH POLES



AT 160A
20 G/CM
RIPPLE ~ 0.1%

1/32 THICK AL. BOTH POLES



AT 200A
20 G/CM
RIPPLE ~ 0.1%

1/32 THICK AL BOTH POLES

FERMILAB ENGINEERING NOTE

SECTION: PSI | PROJECT: PING | SERIAL-CATEGORY: | PAGE:

SUBJECT: NEUTRINO, FAST SPILL, GORDON'S PING MAGNET

NAME: A.T. VISSER

DATE: 3/4/88 | REVISION DATE:

COIL 140 TURNS #9

COIL AVERAGE TURN LENGTH = $66\frac{1}{4}''$

TOTAL WIRE LENGTH = 773 FT, $37\frac{1}{4}$ LBS

COIL WIRE AWG #9, SQUARE, 200°C FILM INSULATED

COIL $R_{20°C} = 0.503\ \Omega$

$R_{90°C} = 0.674\ \Omega$

COIL RATING ~ 18 ADC, 600 V

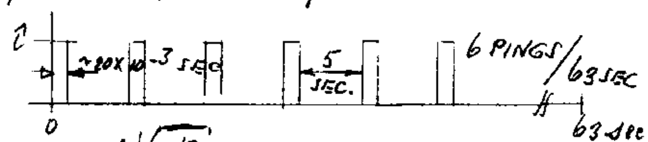
MAGNET GAP $2''H \times 2\frac{1}{16}W \times 25\frac{1}{2}''$ LONG

$B = 6.18$ KG   64.77 cm LONG   4 KGm

$B = \mu_0 H \rightarrow H = \frac{0.618}{4\pi\, 10^{-7}} = 491788\ AT/m$

$AT/_{2''} = 24{,}982$ $N = 140$ $\hat{\imath} = 178.5\ A$

OPERATE



$I_{RMS} \sim \hat{\imath}\sqrt{\frac{.12}{63}} = 7.8\ A$ (24.6 A AT 6x 200 ms PING WIDTH)

$L = \frac{N\Phi}{\hat{\imath}}$ $\frac{140 \times 0.618 \times 0.6477 \times 2.0625 \times 2.54 \times 10^{-2}}{178.5}$

$L = 16.5 \times 10^{-3}$ HENRY

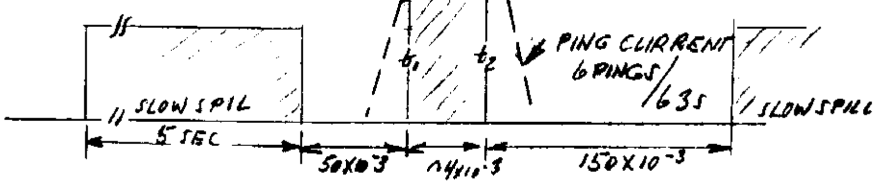
$\frac{1}{2} L \hat{\imath}^2 = 262$ JOULES

STEEL GOOD AT < 100 Hz

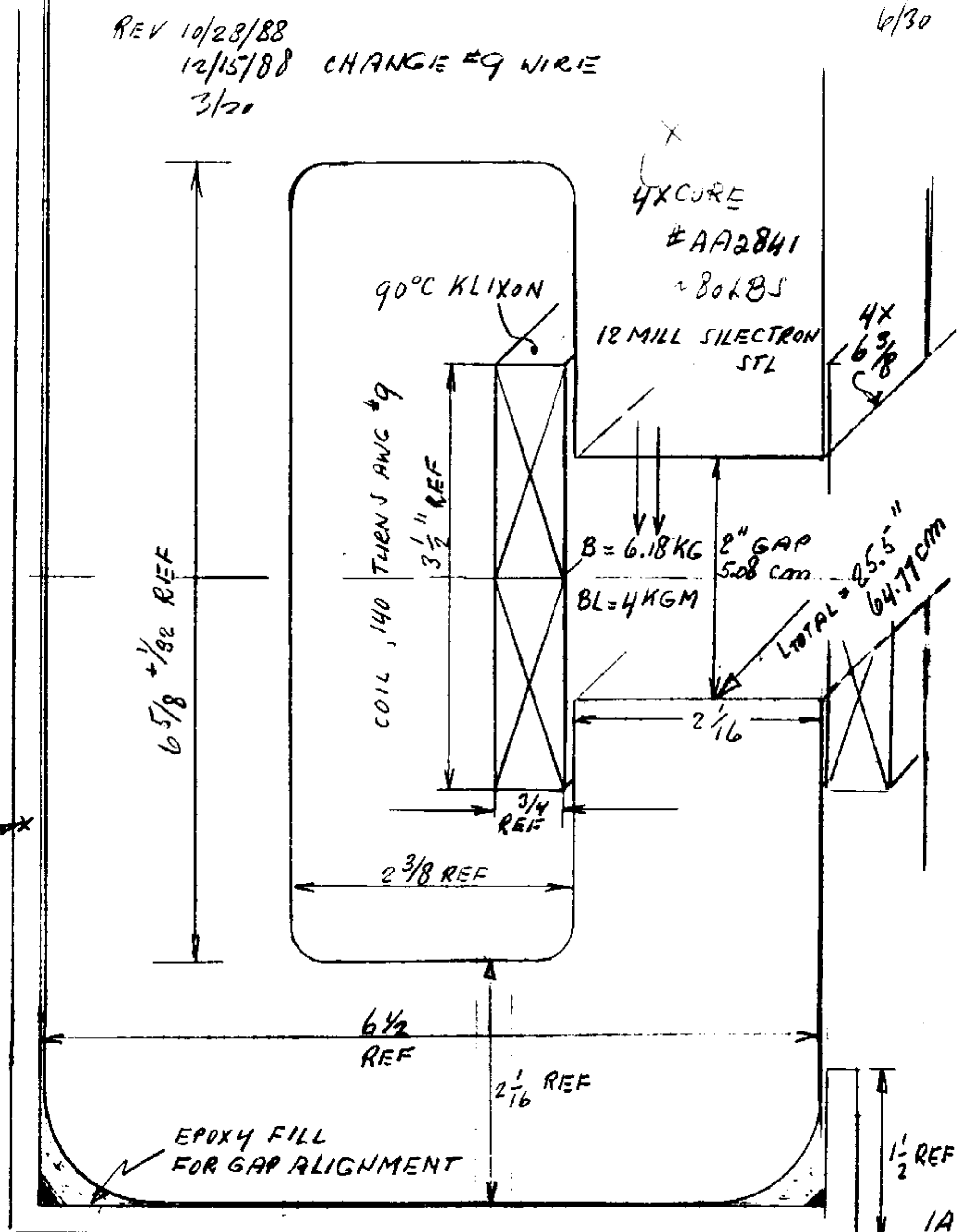
MAGNET WEIGHT ~ 400 LBS

PING WINDOW TYPICAL

REQUIRED PING $\hat{\imath}$ 1% FLAT FOR 4×10^{-3} SEC



CRADLE SH 1C



FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
EED PSI	PING		

SUBJECT: PULSED SADDLE COIL, GORDON'S PING NEUTRINO FAST SPIL

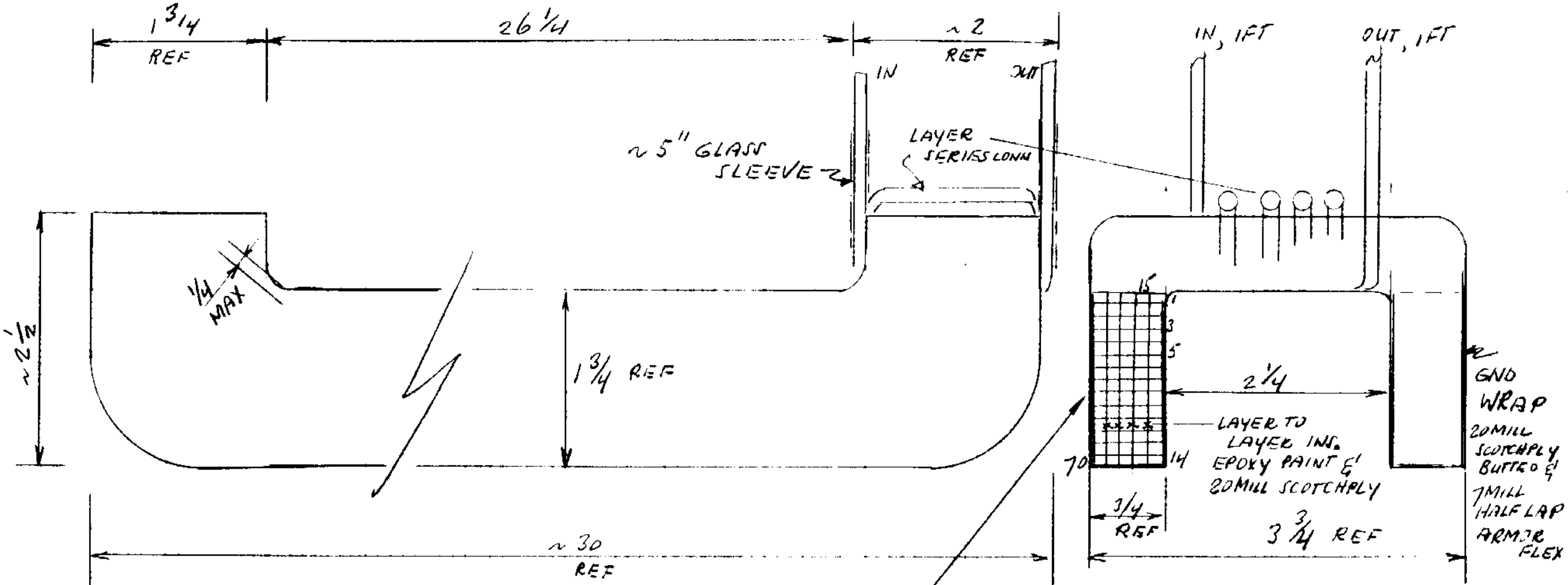
NAME: AT VISSER

DATE: 10/26/88

REVISION DATE:

REV 12/16/88 AWG #9 REDRAWN 6/30

3/20



TYPICAL COIL CROSSECTION

70 TURNS - ESSEX TYPE HGP 200 OR EQUAL
HEAVY POLYESTER AMIDE IMIDE
AWG #9 SQUARE COPPER,
THERMAL CLASS 200 °C, NEMA STANDARD MW36C
390 FT, 19 LBS OF WIRE

QUANTITY: 6 PCS

COIL RATING: ~18 ADC, 200A PEAK AT 300V PEAK
1000 V TO GROUND, $R_{20°C} = 0.252\,\Omega$
155°C HOT SPOT

18

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PSI	PING		

SUBJECT: NEUTRINO FAST SPILL, GORDON'S PING EL POWER SCHEMATIC

NAME: AT VISSER

DATE: 3/10/88 REVISION DATE: 4/11/88

FINAL CHOICE

REV 10/7/88 PREL 6/30 AS BUILD

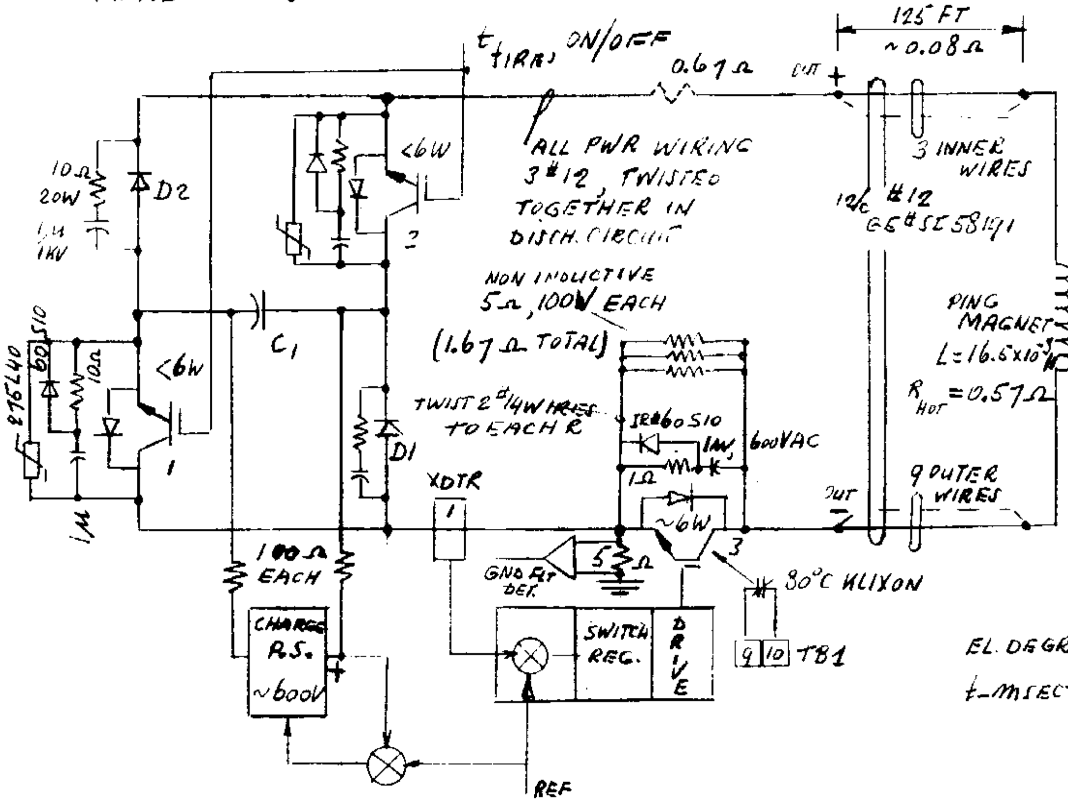
REV 12/15/88 #9 WIRE 3/20/89

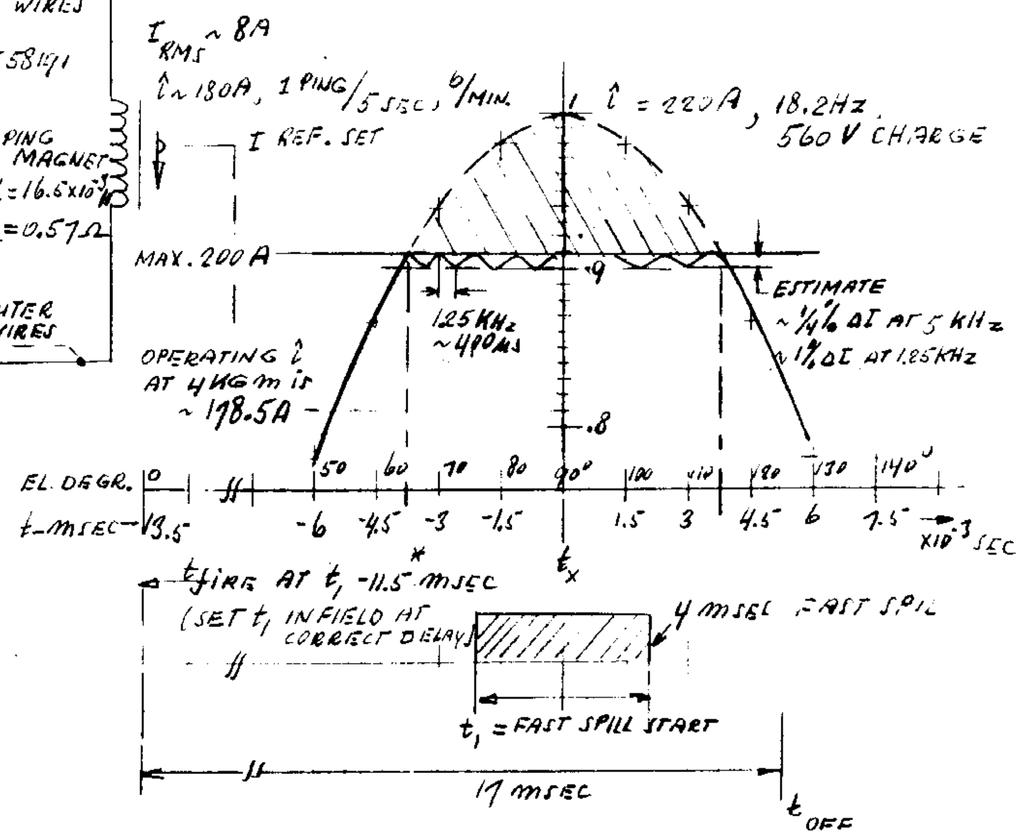
$$f_1 = \frac{1}{2\pi}\sqrt{\frac{1}{LC_1} - \frac{R^2}{4L^2}} = 18.2\ Hz\ *$$

T = 54 x 10^-3 sec; 10^-3 sec = 6.6°

$$\hat{i} = 2\pi f C_1 V_{C1}\, e^{-\frac{R}{8Lf}}\ .76 \qquad V_{C1} = 560V\ *$$

$$\hat{i} = 220\ A\ *$$





1,2,3 - IGBT TOSHIBA # MG 200 N1US1, 1000V/200A

D1, D2 - IR # IRKE 71-12, 1200V/71A

C1 - 4460 μF, 2 x GE 17L 611NJ

XDTR1 - LEM LA 200S - SP24, 200A

/\/\ - 0.67 Ω EST. DISCHARGE LOOP CIRCUIT RESISTANCE

LOSS ~ 6WATT AT 1 200A SHOT/5SEC CONTINUOUS

* CALCULATED VALUES, ACTUAL VALUES MAY DIFFER ~10%

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	PSI	PING		3

SUBJECT: NEUTRINO FAST SPILL, GORDON'S PING CAPACITOR CHARGE CONTROL

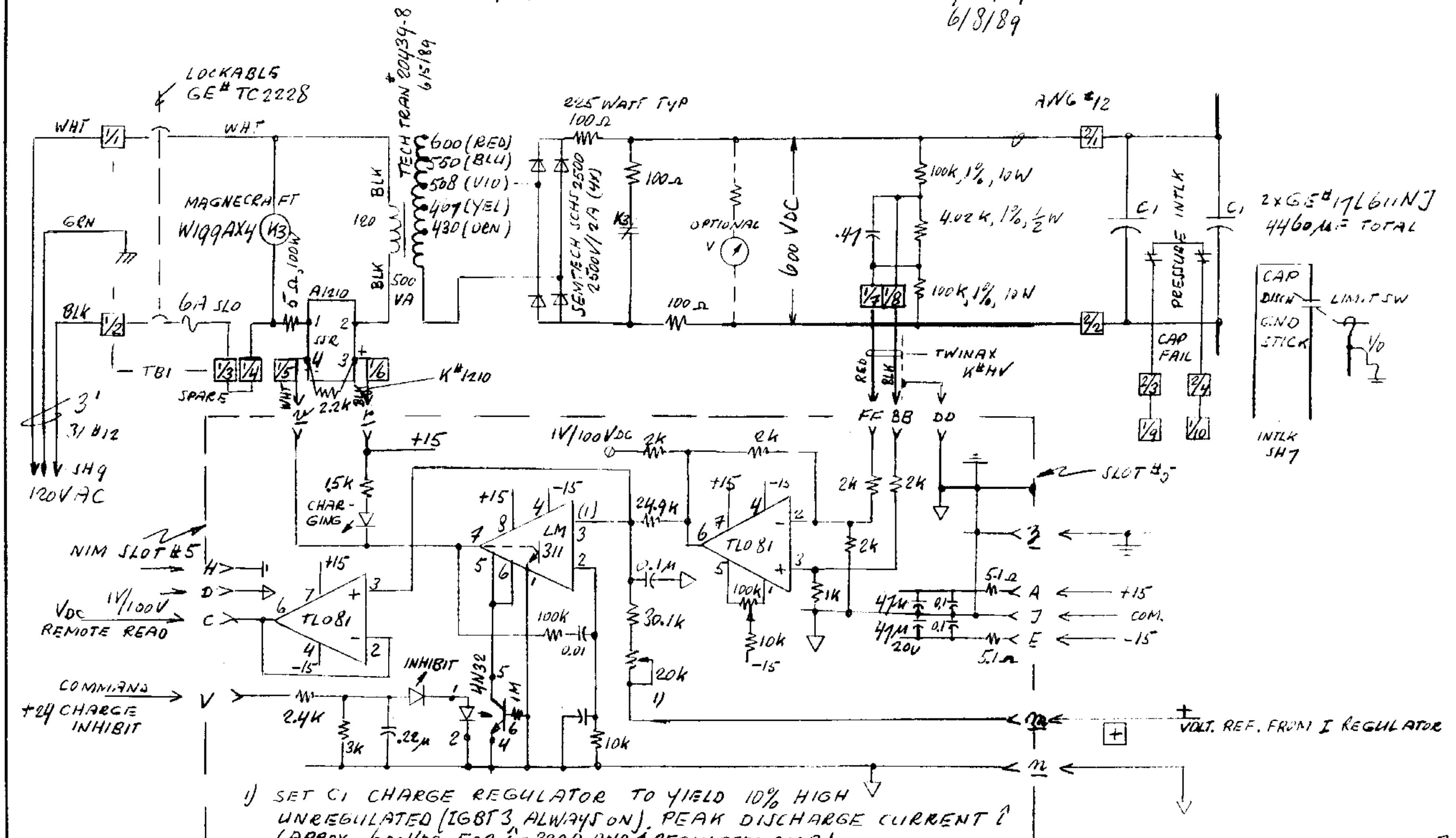
NAME: A.T. VISSER

DATE: 4/18/8?

REVISION DATE:

W. JASKIERNY REV 10/7/88 6/30 AS BUILT
12/15/88
3/20/89
6/8/89

6/30



1) SET C1 CHARGE REGULATOR TO YIELD 10% HIGH UNREGULATED (IGBT3 ALWAYS ON). PEAK DISCHARGE CURRENT $\hat{i}$ (APROX. 600VDC FOR $\hat{i}$ = 220A AND $\hat{i}$ REGULATED 200A)

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PSI	PING		

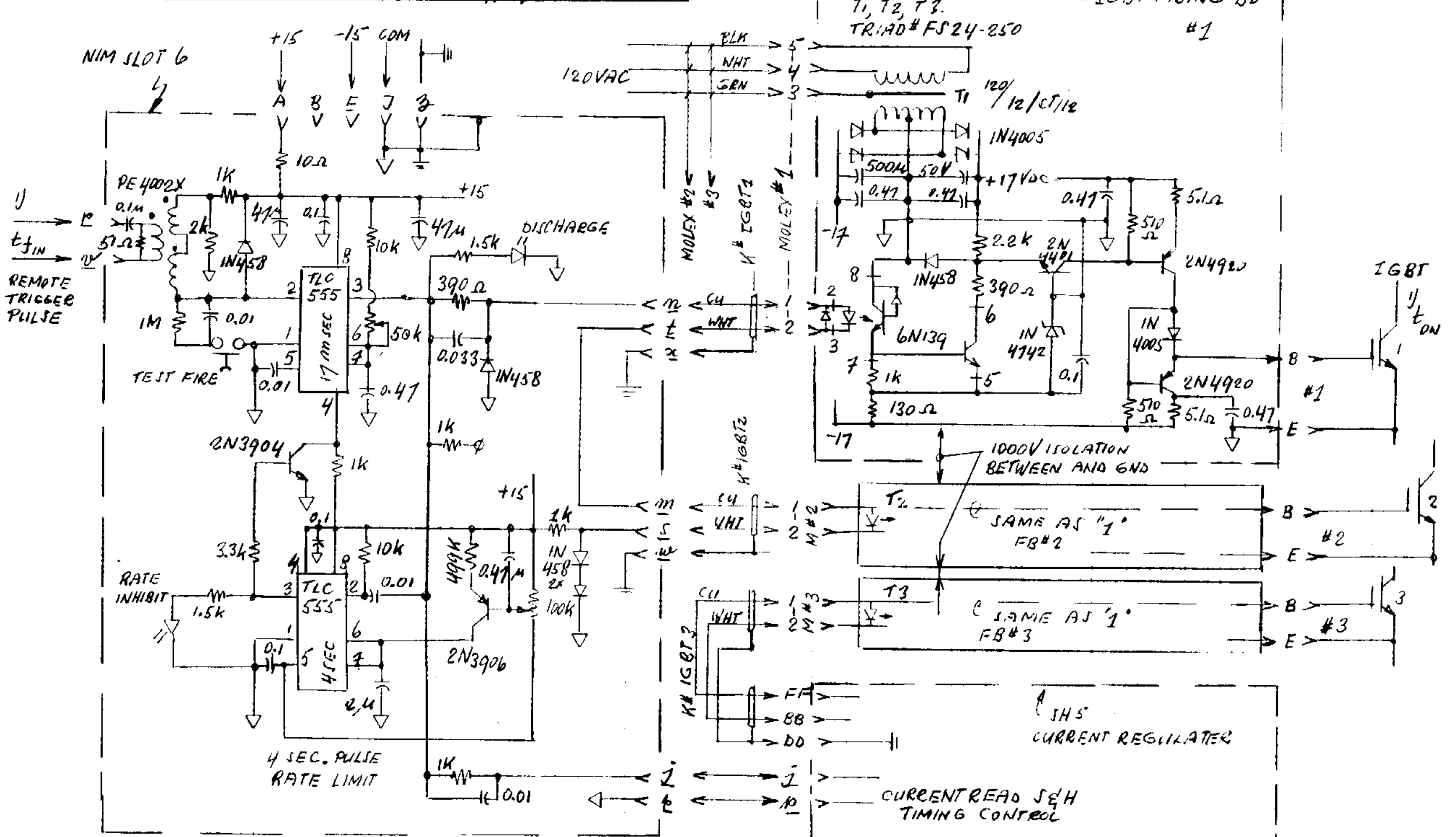
SUBJECT: NEUTRINO FAST SPIL, GORDON'S PING FIRING CONTROL

NAME: A.T. VISSER

DATE: 4/20/88

REVISION DATE:

REV 10/7/88 W. JASKIERNY 6/30 AS BUILD 6/30
12/10 , 3/20/89



NOTE 1): MEASURED DELAY BETWEEN $t_{fIN} - t_{ON}$ is ~ 1 μSEC

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PSI	PING		

SUBJECT: NEUTRINO FAST SPILL, GORDONS PING CURRENT REGULATOR

NAME: A.T. VISSER

DATE: 4/20/88

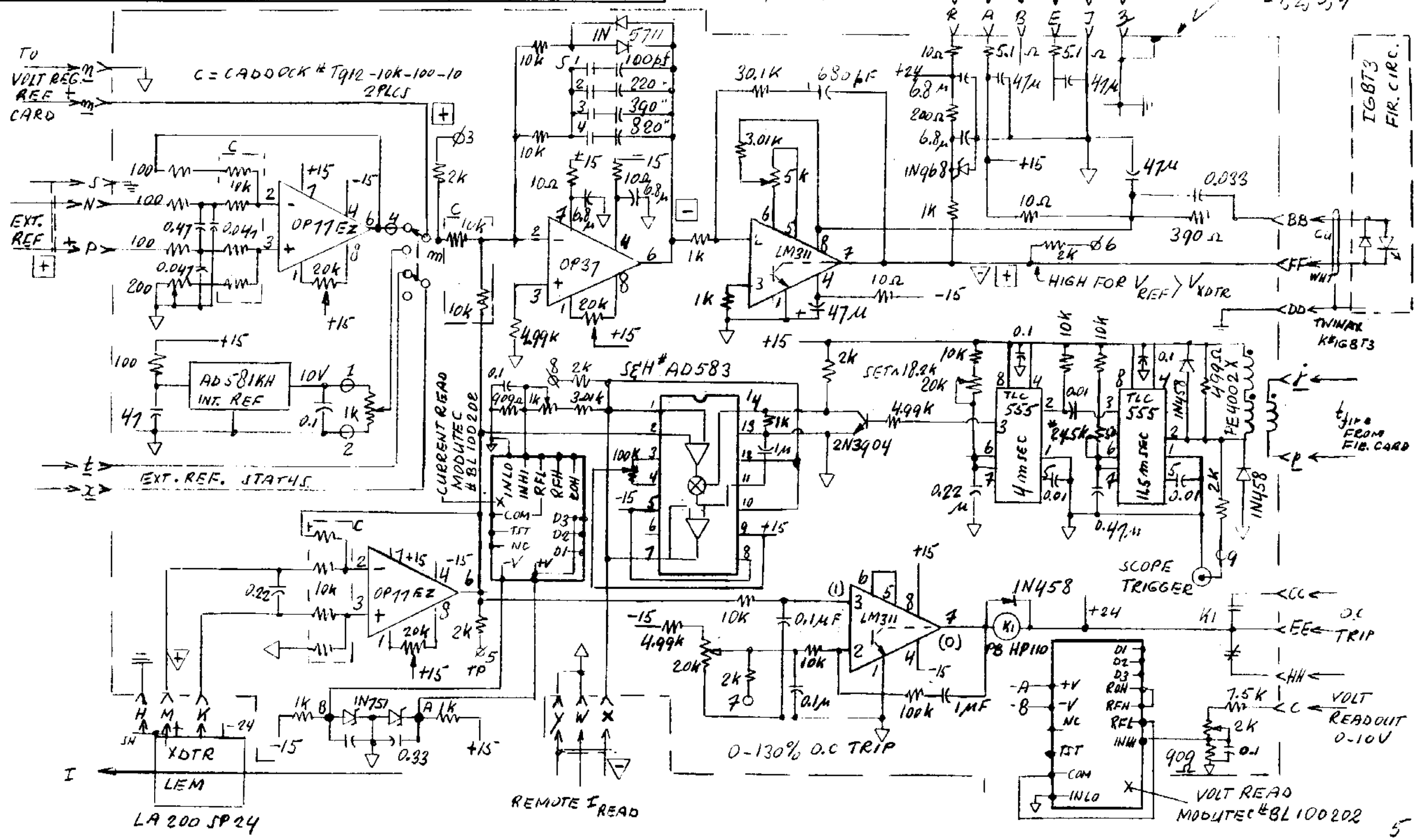
REVISION DATE

REV 10/7/88 W. JASKIERNY

3/20/89

6/30 AJ Build

6/30



5

FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PSI	PING		

SUBJECT: NEUTRINO FAST SPIL, GORDON'S PING A.C. TYPE GND FLT DETECTOR

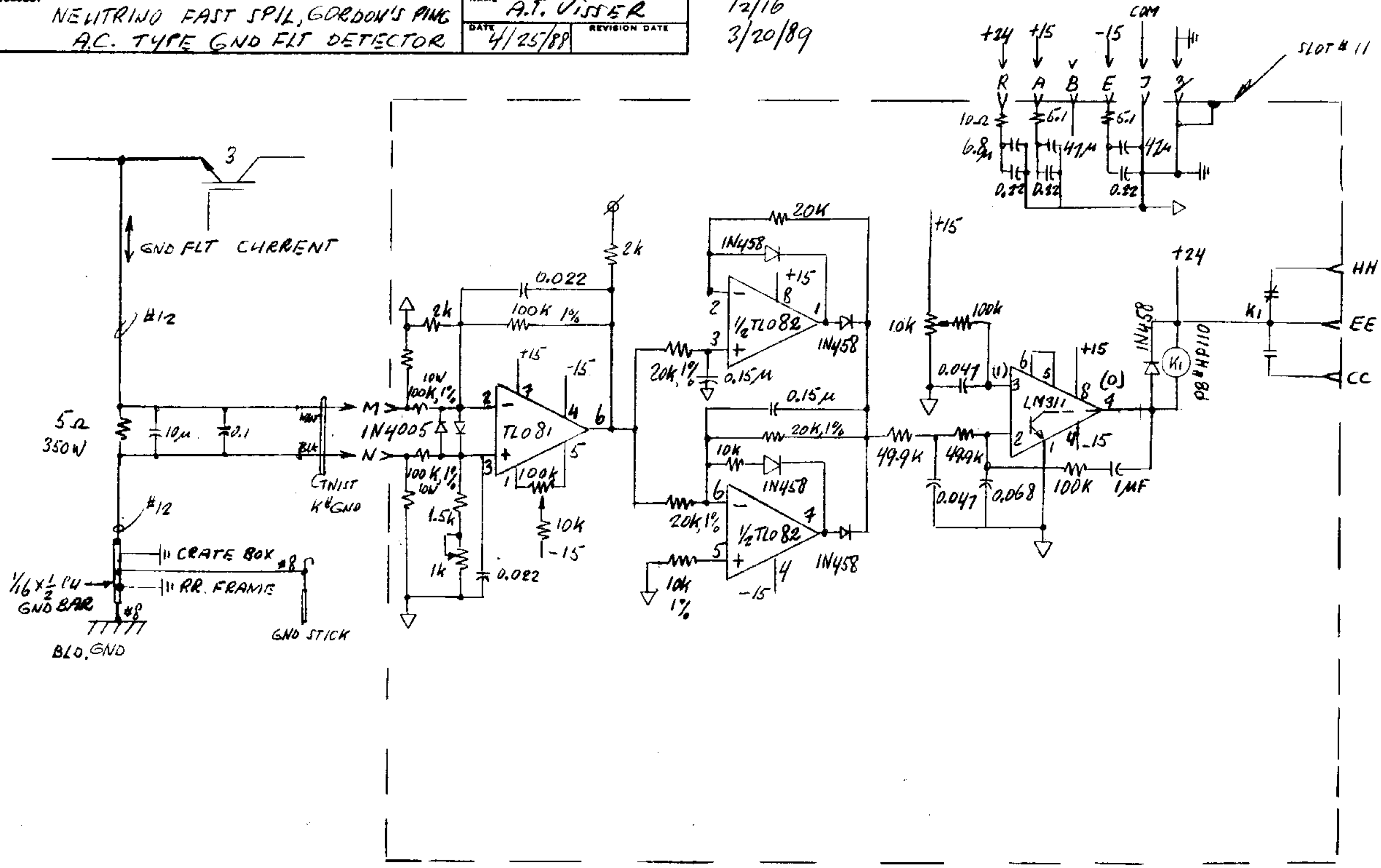
NAME: A.T. VISSER

DATE: 4/25/88

REVISION DATE:

REV 10/7/85 W. JASKIERNY
12/16
3/20/89

6/30



FERMILAB ENGINEERING NOTE

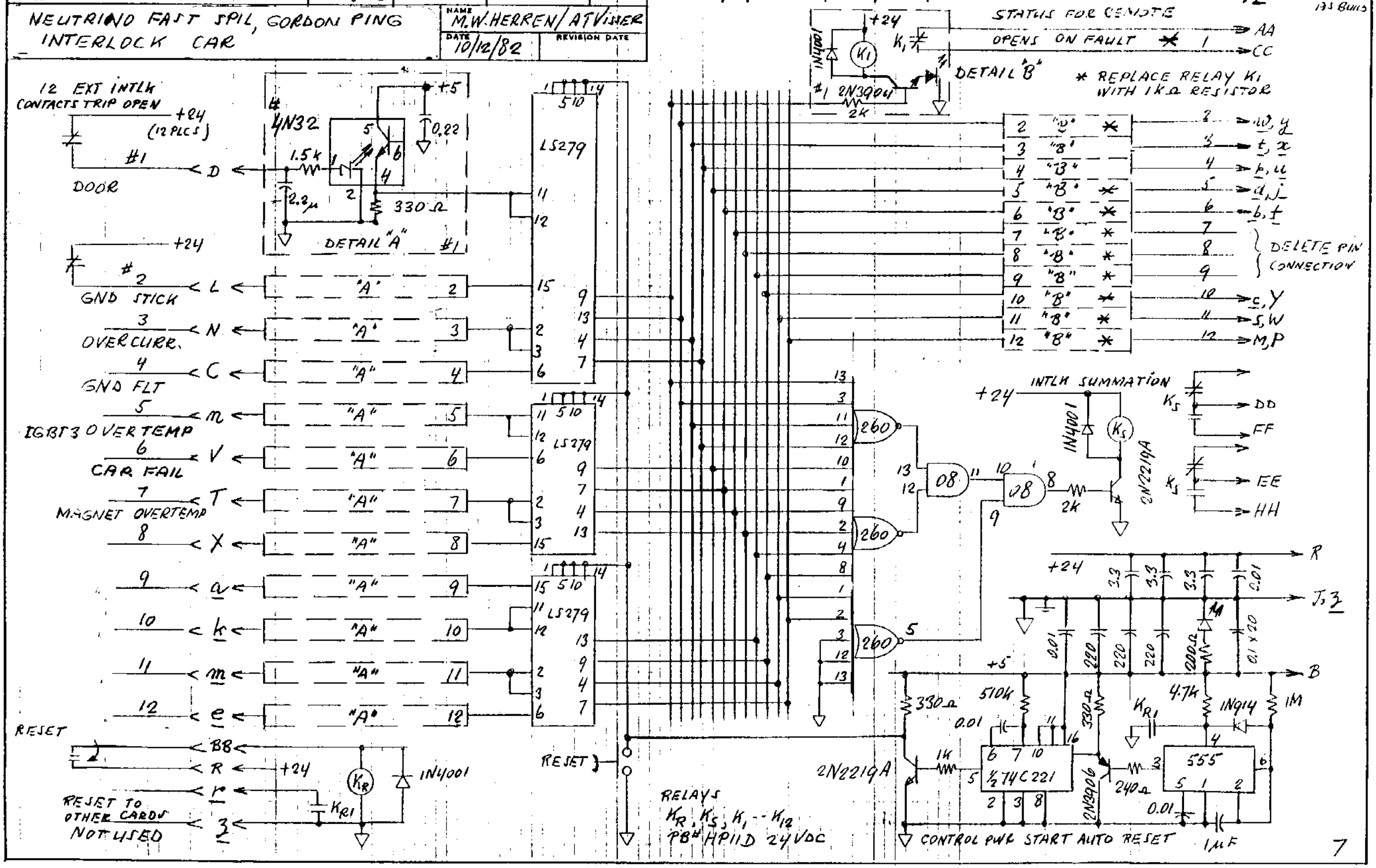
SECTION	PROJECT	SERIAL-CATEGORY	PAGE
EA, PSI	PING		

NEUTRINO FAST SPIL, GORDON PING INTERLOCK CAR

NAME: M.W. HERREN / AT Visser

DATE: 10/12/82 REVISION DATE

DRW# 2789-EC-172034 SH7 REV 10/1/81, 3/20/89 SLOT 12 6/30 135 Bulls



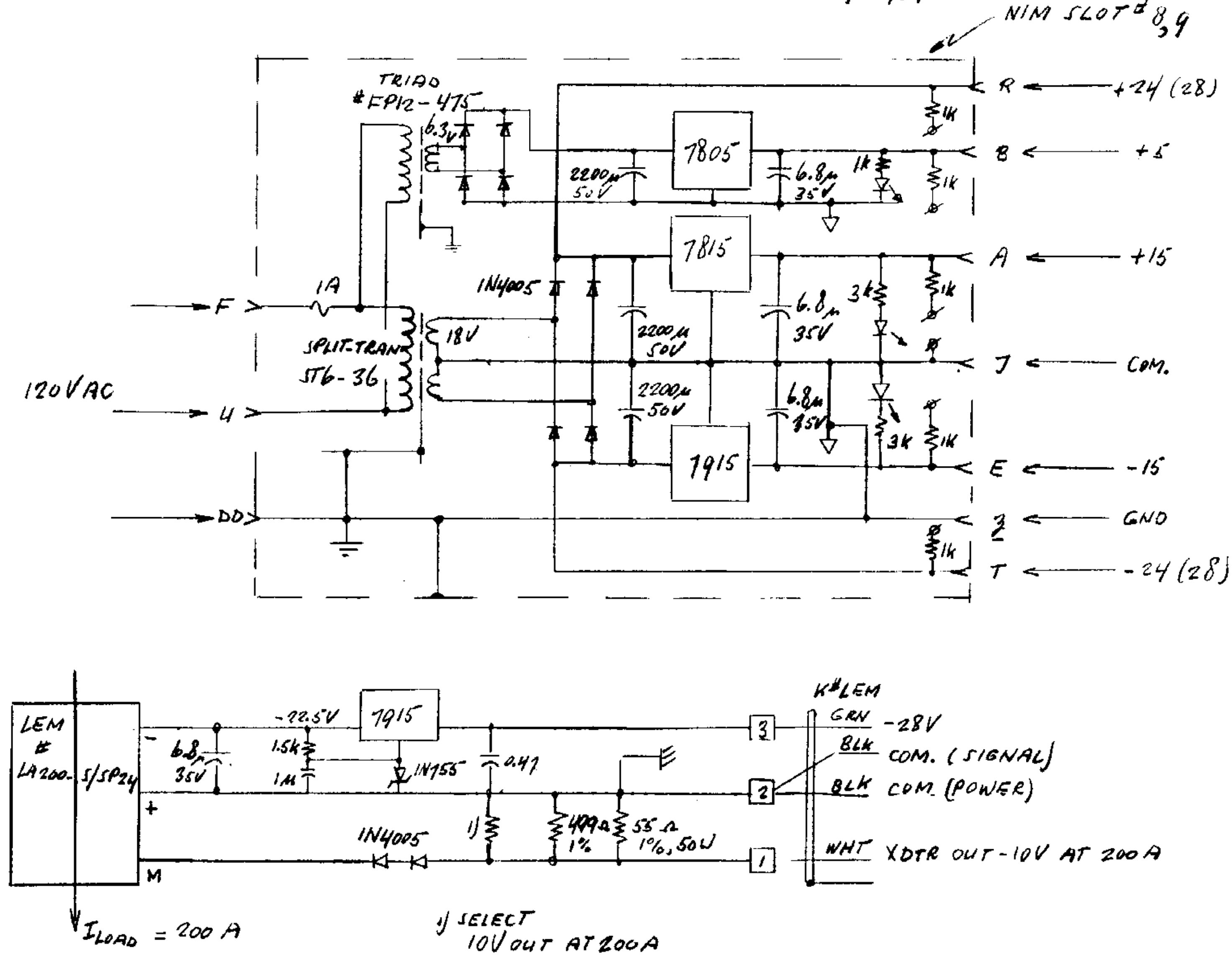
7

FERMILAB ENGINEERING NOTE	SECTION: PSI	PROJECT: PING	SERIAL-CATEGORY:	PAGE:
SUBJECT: NEUTRINO FAST SPILL, GORDON & PING CONTROL PWR, AND LEM CIRC.	NAME: A.T. VISSER	DATE: 4/26/88	REVISION DATE:	

REV 10/7/88
12/15
3/20/89

AS BUILD 6/30

6/30



FERMILAB ENGINEERING NOTE

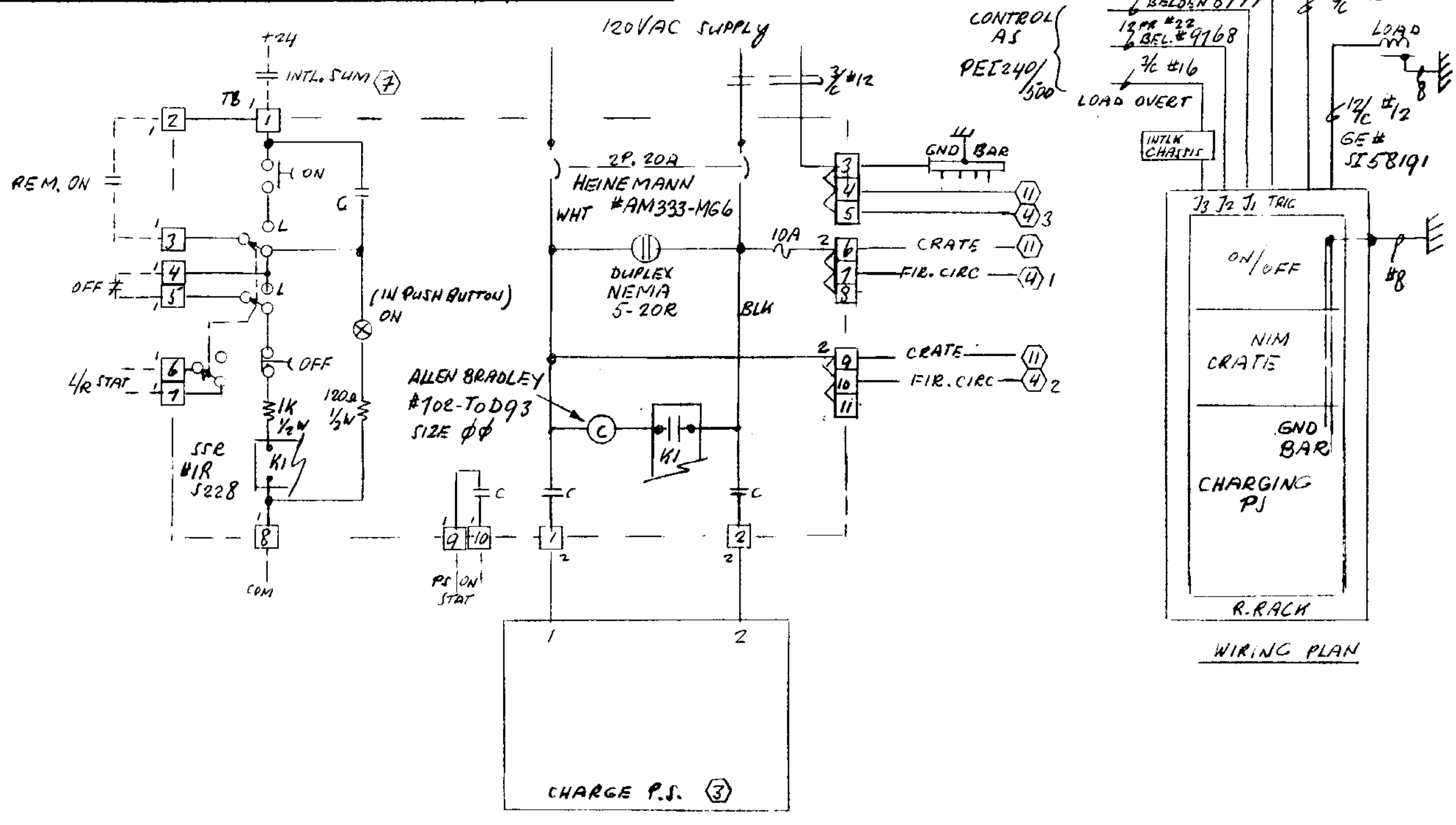
SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PSI	PING		

SUBJECT: NEUTRINO FAST SPILL, GORDON'S PING RR. CONTROL AND WIRING PLAN

NAME: A T VISSER

DATE: 1/27/88

REVISION DATE:



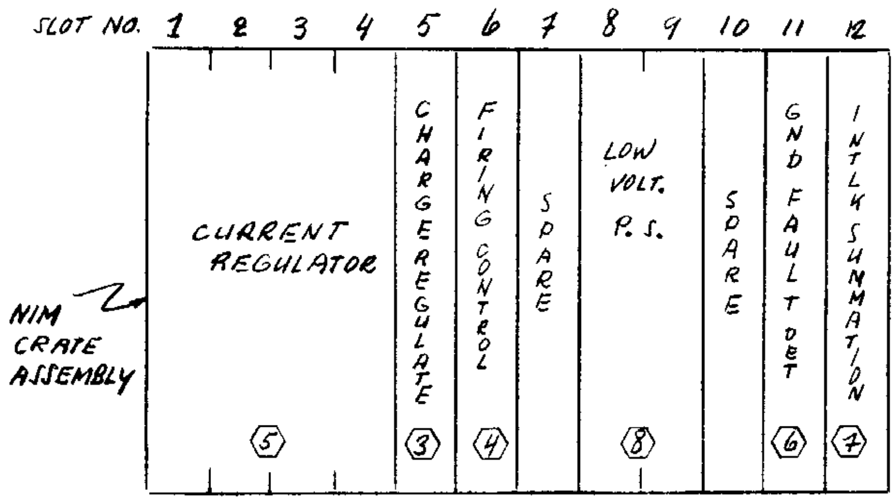
FERMILAB ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PSI	PING		

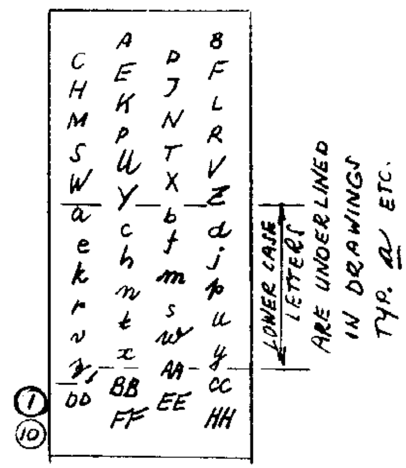
SUBJECT: NEUTRINO FAST SPILL, GORDON'S PING
NIM CRATE ASSEMBLY DETAILS

NAME: A.P. VISSER
DATE: 4/29/88
REVISION DATE:

6/30

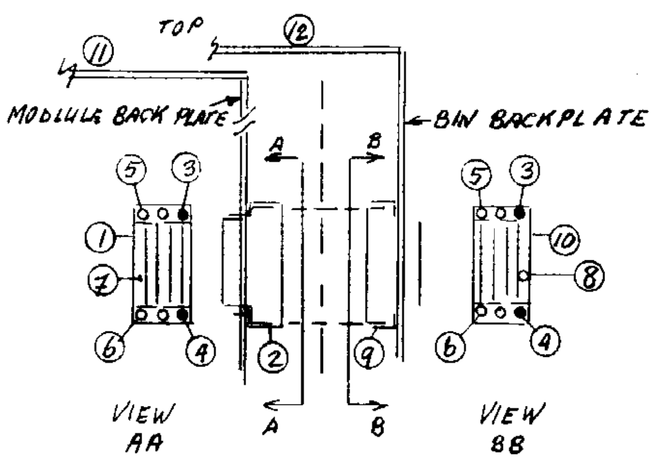


FRONT VIEW



CONNECTOR BLOCK NUMBERS VIEW BB

ITEM	DESCRIPTION	AMP PART NO	NAL STOCK NO
1	CONNECTOR BLOCK, MODULE	201358 - 3	1431 - 1001
2	PIN HOOD INTERNAL	202394 - 2	" - 1070
3	GUIDE PIN GOLD	202514 - 1	" - 1025
4	GUIDE PIN CAD.	200833 - 4	" - 1015
5	GUIDE SOCKET GOLD	202512 - 1	" - 1030
6	GUIDE SOCKET CAD	200835 - 4	" - 1020
7	#16-#18 PIN	200336 - 1	" - 1045
8	#16-#18 SOCKET	200333 - 1	" - 1050
9	PIN HOOD EXTERNAL	201390 - 5	" - 1065
10	CONNECTOR BLOCK BIN	200277 - 4	- 1000
11	SINGLE WIDTH MODULE COMPLETE, LESS CONNECTOR		1440 - 4100
12	NIM CRATE		



NIM - DETAILS

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE
	PSI	PING		

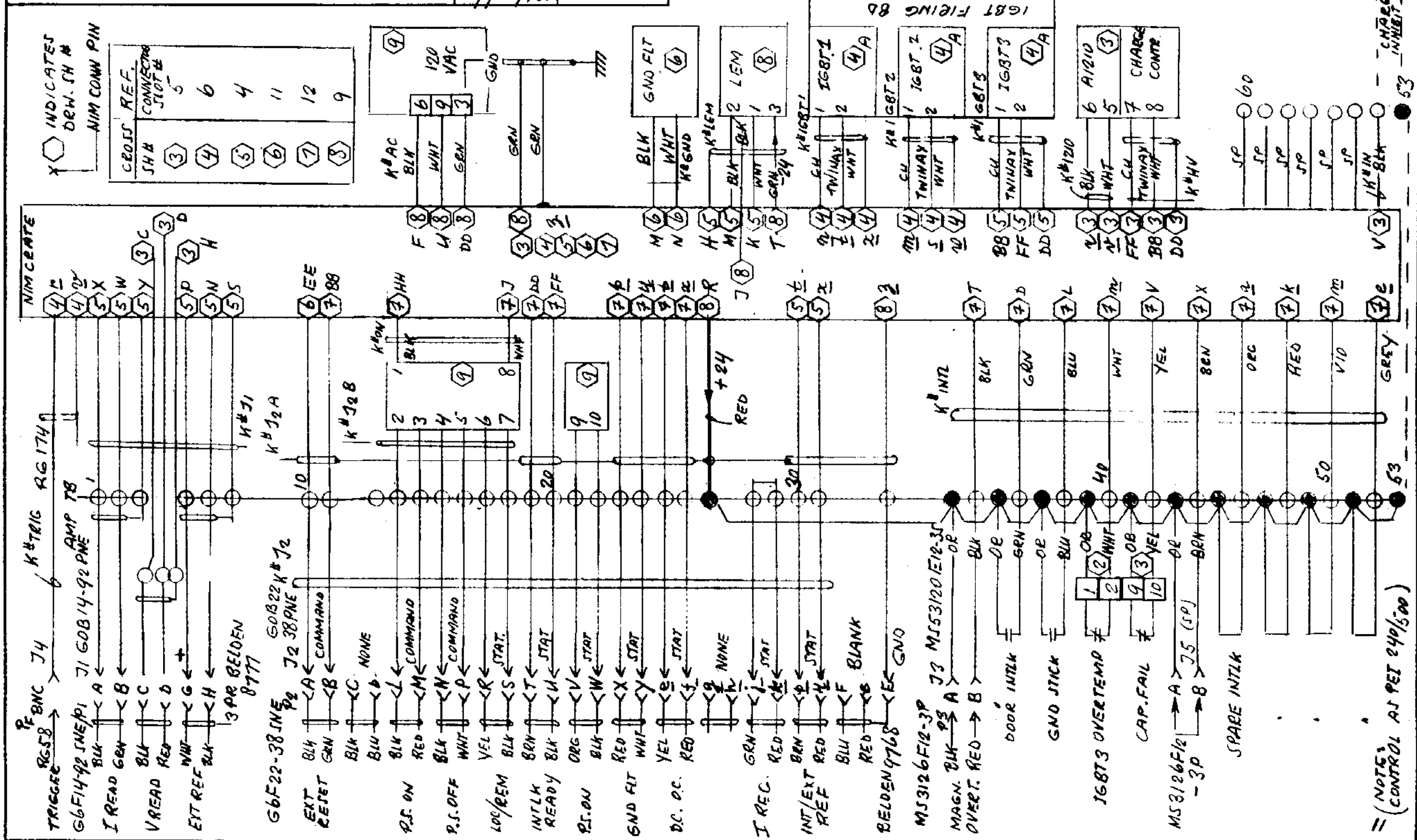
SUBJECT: NEUTRINO FAST SPILL, GORDON'S PING
EXT. CRATE CONNECTIONS

NAME: A.T. VISSER
DATE: 4/27/88
REVISION DATE:

REV 10/7/88
12/15
3/20/89

AS BUILD 6/30

6/30



FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
PSI	PING		

SUBJECT: NEUTRINO FAST SPIL, GORDON'S PING CRATE WIRING INTERNAL REAR VIEW

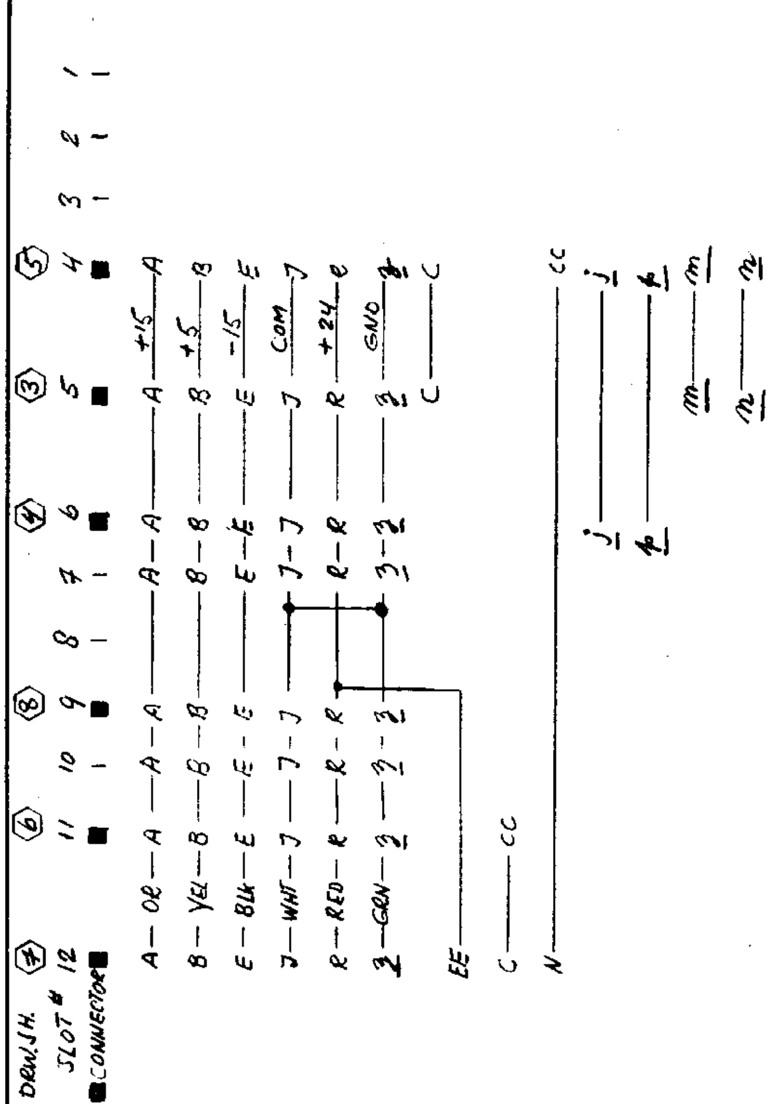
NAME: A.T. VISSER

DATE:

REVISION DATE:

REV 10/7/88
12/15
1/10 DELETE EXT CONNECTIONS
3/20/89
6/30 AS BUILD

6/30



12